AD NUMBER
AD889246
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; SEP 1971. Other requests shall be referred to Air Force Materials Lab., Wright-Patterson AFB, OH 45433.**
AUTHORITY
AFWAL ltr 19 Nov 1982

AD 889246

AUTHORITY: AFWAL

ltr, 19NOV82

AFML-TR-71-184

AD 889246

FRETTING RESISTANT COATINGS FOR TITANIUM ALLOYS

D.J. Padberg
McDonnell Aircraft Company

TECHNICAL REPORT AFML-TR-71-184

SEPTEMBER 1971

Distribution limited to U.S. Government agencies only; Test and Evaluation; 13 September 1971. Other requests for this document must be referred to the Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

FRETTING RESISTANT COATINGS FOR TITANIUM ALLOYS

D.J. Padberg
McDonnell Aircraft Company

FOREWORD

This Final Technical Report covers all work performed under U.S. Air Force Contract No. F33615-70-C-1538 from 18 May 1970 to 18 June 1971. The manuscript of this report was submitted by the author on 18 July 1971 for publication.

This project was performed by the Material and Process Development Department, Aircraft Engineering Division, McDonnell Aircraft Company (MCAIR) under Materials Laboratory Project 7312, "Metal Surface Deterioration and Protection for Advance Air Force Weapon Systems Components." It was accomplished under the technical direction of Mr. Jesse Crosby of the Metals Branch (LLP), Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. E. R. Fannin, Section Manager, Material and Process Development Department, was the program manager. D. W. Lum and D. J. Padberg were in charge of the technical effort. D. J. Thies (specimen design analysis) and G. W. Wille (laboratory testing) contributed to major portions of the work performed.

This technical report has been reviewed and is approved.

I Perlmutter

I. Perlmutter
Chief, Metals Branch
Metals and Ceramics Division
Air Force Materials Laboratory

ABSTRACT

This report describes a program undertaken to establish the effect of airframe design parameters upon the severity of fretting in titanium structures and to determine the ability of selected coatings to prevent fretting induced fatigue failures. The program was performed in three tasks.

Task I began with a survey of aircraft structures establishing the design limits of those parameters which can influence fretting. A test specimen was designed to simulate a structural joint and a series of fatigue tests was performed to determine the conditions most conducive to fretting initiated failure. It was found that at low stress levels and using tapered interference fit fasteners, the number of fatigue cycles accumulated to the point that fractures originated from fretting damage. These latter parameters were chosen for test of coated specimens in Task III.

Task II consisted of a survey of titanium coatings technology and testing and selection of three coatings for use in Task III. On the basis of their properties and minimal degradation of Ti-6Al-6V-2Sn fatigue resistance, a chemical conversion coating and a commercial anodize coating were chosen along with a dry film lubricant.

Task III consisted of fatigue tests of Ti-6Al-6V-2Sn specimens protected by the coatings from Task II. The coatings essentially eliminated the fretting induced fatigue failures of Task I. Final coating performance verification tests on Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo specimens demonstrated the same improvement using dry film lubricant applied to a shot peened surface.

TABLE OF CONTENTS

LIST OF PAGES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

1.0 INTRODUCTION

Titanium alloys will comprise 30% - 50% by weight of the primary structure of the next generation fighter aircraft. Their increased use is based on high temperature resistance, high strength to weight ratio, good fatigue properties and excellent corrosion resistance. Like other high strength alloys used in airframe construction, titanium is susceptible to fretting damage. Such damage may weaken a structure and possibly cause premature fatigue failure. Because of its known tendencies to seize and gall titanium could possibly be critical in this regard.

Early MCAIR investigations showed that fretting must be taken into consideration as a factor influencing fatigue life. The ultimate severity of fretting damage discovered in those studies is illustrated in Figure 1. The normal point of highest stress concentration on this stringer to rib joint should have been the fastener hole. As evidenced by the fact that the line of failure did not pass through the hole, the fracture originated on the faying surface at the point of fretting damage.

Historically, the fretting fatigue of high strength alloys has been alleviated by preventing contact between the surfaces. This approach includes insertion of bushings and application of coatings and surface treatments. Because minimum work has been performed for titanium the overall purpose of this program was to investigate surface treatments and coatings for titanium to alleviate fretting fatigue. These coatings should be adherent and capable of application to complex shapes. In addition, these coatings must not impair the mechanical properties of the titanium substrate.

This program was divided into three tasks and included the establishment of fretting conditions in titanium joints, selection of candidate coatings for titanium to prevent fretting damage and coating evaluation in a fretting-fatigue critical joint.

Bare Specimen

GP71-0879-25

Figure 1 Fatigue Failure Due to Fretting Damage

2.0 SUMMARY

An initial survey was performed of F-4J/E, DC-10, and F-15 structural joint designs for actual limits of stresses, clamp-up loads, alloys, and types of fasteners. This data was incorporated into the design of a test plan and a fatigue specimen simulating a structural joint. Specimens were fabricated from Ti-6Al-6V-2Sn annealed plate with special attention to maintaining similar surface condition and fastener hole preparation on all specimens as in normal manufacturing operations. All material was chem-milled prior to fabrication. Hole drilling was followed by hand reaming to obtain a 32 rms finish and the close tolerance required on fastener holes.

In Task I fatigue tests of uncoated dogbone specimens (attached plates on each side), failures originated at the point of highest stress concentration, the fastener holes, under 70.4 ksi stress with clearance fit fasteners. Fracture occurred as early as 12,000 cycles. Even at low stress (38.4 ksi), failures with clearance fit fasteners originated at the hole after 112,000 cycles average and were not associated with fretting damage. However, the combination of tapered interference fit fasteners, low load transfer, and low stress level extended the fatigue endurance of the specimen to the point that fretting damage became critical. Under these conditions, fractures originated at the fretted areas on the faying surfaces. Average cycles to fretting fatigue failure was 270,000.

Task II evaluated commercially available coatings and surface treatments for titanium alloys and surveyed research literature and the work of private laboratories pertaining to fretting protection. Based on the reported characteristics of the coatings, their cost and ease of application, and their effect on properties of the titanium substrate, 11 wear coatings and 3 lubricant coatings were selected for screening tests. Test strips of these coatings were evaluated for adhesion to the substrate, micro-structure, hardness, and effect on hydrogen content of the titanium. Tensile and fatigue properties were determined on Ti-6Al-6V-2Sn coated by nine of the processes. The final choice of coatings for Task III testing was based largely on their minimal effect on fatigue properties. Of the coatings tested only the fluoride-phosphate conversion coating and Tiodize II commercial anodize did not cause a significant drop in fatigue properties. Because of their relatively poor wear resistance, both coatings were used with Molykote 106 lubricant. For the third coating system of Task III, Molykote 106 was chosen for application directly to the titanium alloy.

Task III consisted of testing three groups of Ti-6Al-6V-2Sn fatigue specimens, each group coated with one of the coating systems selected in Task II. All specimens were shot peened and grit blasted prior to coating. Based on Task I, these specimens used Taper-Lok fasteners (Ti-6Al-4V), permitted low load transfer and were subjected to axial tension-compression fatigue tests ($R = -0.1$) using a maximum gross stress of 38.4 ksi and a cyclic frequency of 30 cps. All the specimens exceeded 2.5 million cycles without failure. Since dry film lubricant without prior bond coating was the least expensive and easiest to apply of the three coatings systems tested, it was selected for test on additional test specimens of Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo. These tests also ran beyond 2.5 million cycles without failure. Under these test conditions, dry film lubricant proved to be an effective method of eliminating fretting induced fatigue failures.

3.0 ESTABLISHMENT OF FRETTING CONDITIONS, TASK I

Certain conditions, such as cyclic relative motion and pressure between members, are required for fretting wear to occur. Strain-induced movement in aircraft structures increases the possibility that fretting damage may occur between the growing number of members that are being designed using titanium alloys. Many design conditions will affect the amount of strain and relative motion between members. The interaction between fretting damage and fatigue can be reliably evaluated only by fatigue testing of specimens representative of actual structure. Therefore, the purpose of Task I was to determine the combination of those design conditions most likely to be associated with fretting initiated fatigue failure.

The first consideration in designing a fatigue test was to be certain the simulated structural conditions would represent actual design. A survey was made of airframe joints for potential fretting sites. Using the design parameters typified in this survey, a test specimen was developed to simulate a structural joint while allowing adjustment of test parameters within certain limits. A series of fatigue tests was conducted. Based on the number of cycles required to produce fretting initiated fatigue fracture, one set of conditions was determined to be most likely to result in fretting-fatigue failure unless protective precautions are taken. These parameters were selected for additional testing of coated specimens in Task III.

3.1 Airframe Joint Survey - Fretting originates at structural joints where relative motion can induce damage during cyclic loading.

Three kinds of structural joints where fretting might be a factor are:

a) Low Shear Transfer, e.g., skin-stringer interfaces

b) High Shear Transfer, e.g., longeron-stringer splices

c) Complete load transfer, e.g., pin-loaded lug ends

Pin-loaded lug joints (100% of the load transferred through the pin) typically represent a much smaller total weight in an aircraft than the first two type joints and there are usually no critical weight penalties to prevent slight overdesign sufficient to obviate fretting-fatigue failure. For this reason, as well as the fact that each lug is a special design for its particular application and not amenable to general categorizing, pin loaded lugs were excluded from the survey. Listed in Table I are examples of the other two types of joints which were surveyed on the F-4J/E, DC-10, and F-15 designs.

Figure 2 depicts an assembly of a leading edge skin to the main box of a stabilator structure employing Ti-6Al-4V screws to join 2024-T81 aluminum to Ti-6Al-4V. Figure 3 is typical of a high shear load in a Taper-Lok fastener used on a wing skin splice joint. Application of a Hi-Lok fastener in a typical splice of Ti-6Al-6V-2Sn longeron is shown in Figure 4. A splice typical of the large wing spars in commercial aircraft is shown in Figure 5.

Table I Typical Design Parameters - Titanium Airframe Joints

Joint	Structural Material	Fastener	Design Torque Range (In. Lb)	Fastener Clearance Max / Min	** Joint Cyclic Frequency	Joint Stress Levels (Based on Load Spectrum) (KSI)
Stabilator Torque Rib	Ti-6-4 Plate, Ti-6-6-2 Rib	Ti Screw (7/16)	270 to 300	0.0022 / 0.0000	Low	9 to 115
Stabilator Skin Splice	Ti-6-4, 2024-T81	Ti Screw (3/16)	20 to25	0.0022 / 0.0000	Low	9 to 115
Bulkhead Splice	Ti-6-6-2, 4 Pieces	Ti TaperLok (1/4)	120 to 140	0.0045* / 0.0035	Low	21 to 100
Wing Rib Splice to Stringer	Ti-6-6-2, 2024-T851	Ti HiLok (5/32)	50 to 70	0.0022 / 0.0000	Low	21 to 100
Wing Skin Splice	Ti-6-6-2, 2024-T851	Ti TaperLok (1/4)	120 to 140	0.0045* / 0.0035	Low	21 to 100
Wing Skin to Spar	Ti-6-6-2, 2 Pieces	Ti TaperLok (1/4)	120 to 140	0.0045* / 0.0035	Low	21 to 100
Longeron Splice	Ti-6-6-2	Ti HiLok (1/4)	50 to 70	0.0022 / 0.0000	Low	21 to 100
Sweepback Skin to Stringer	2024-T351 7075-T6511	Steel TaperLok (5/16)	150 to 200	0.004* / 0.0005	Low	22
Skin to Stringer	2024-T351, 7075-T6511	Steel TaperLok (5/16)	150 to 200	0.004* / 0.0005	Low	22
Rear Spar Splice	7075-T73, 2024-T351	Ti TaperLok (5/16)	150 to 170	0.0048* / 0.0028	Low	16

GP71-0879-16

* Interference Fit or TaperLok Fastener
** "Low" — Less than 1 cps

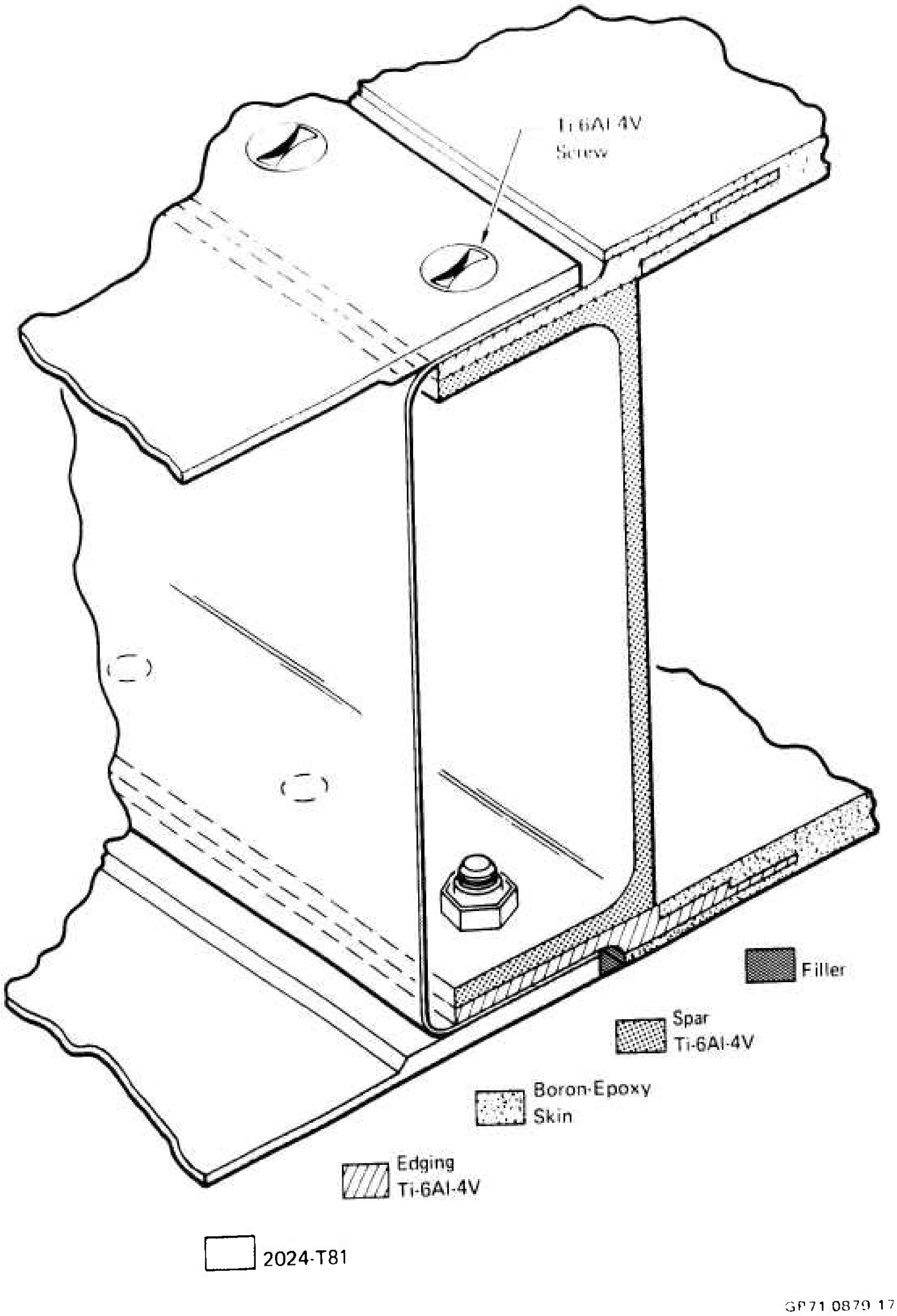


Figure 2 Stabilator Skin Splice Assembly

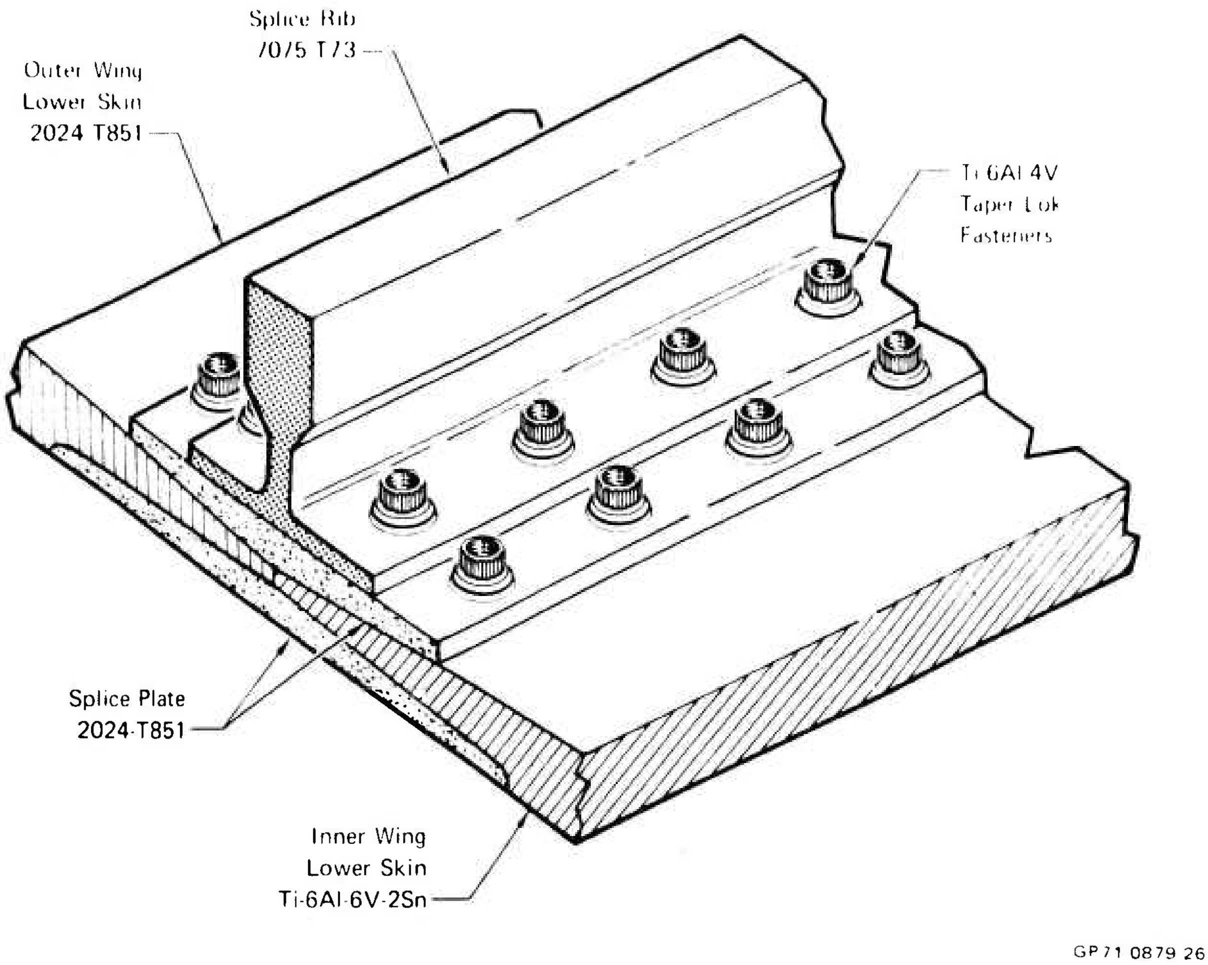


Figure 3 Assembly of Wing Skin Splice

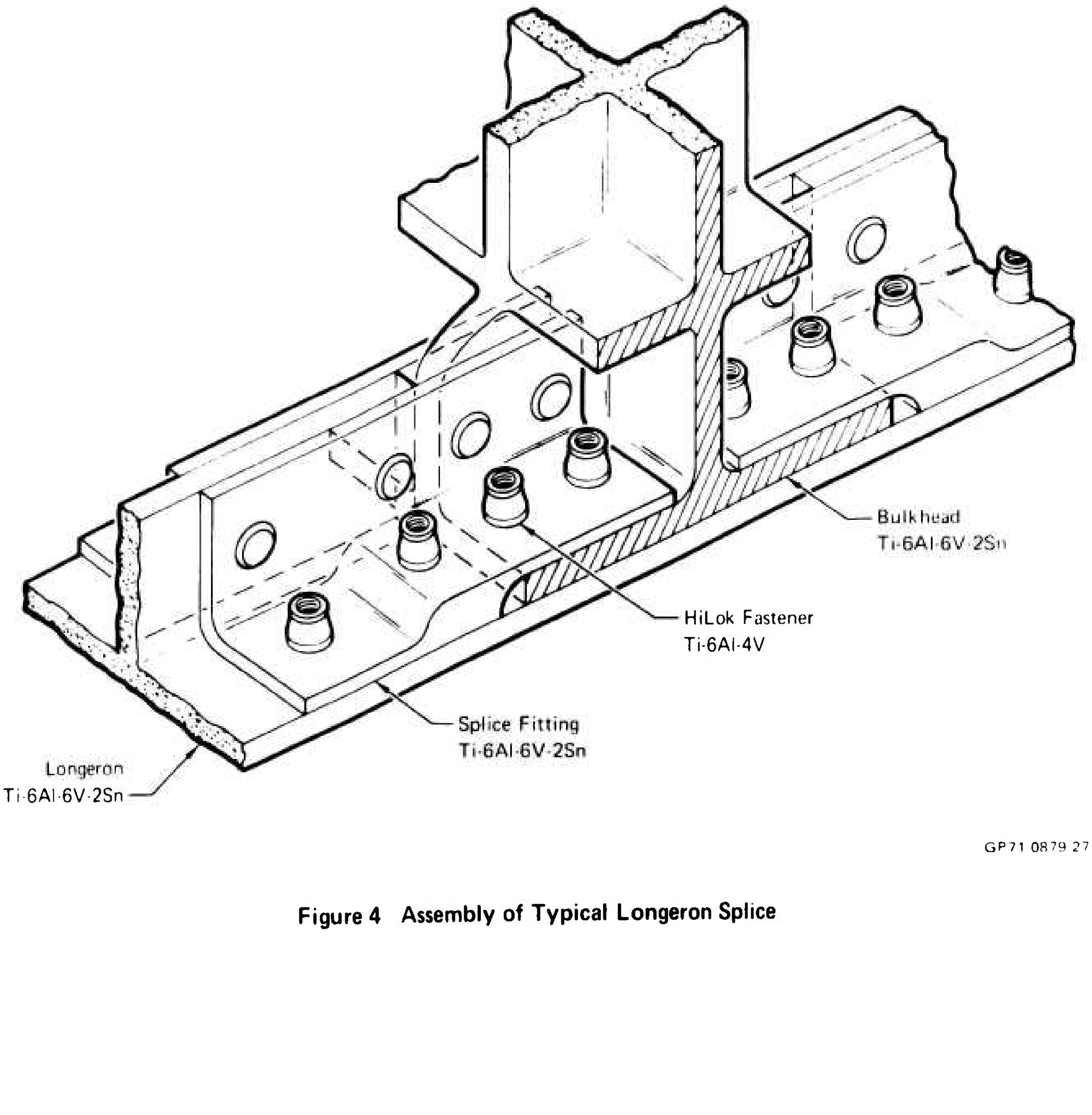


Figure 4 Assembly of Typical Longeron Splice

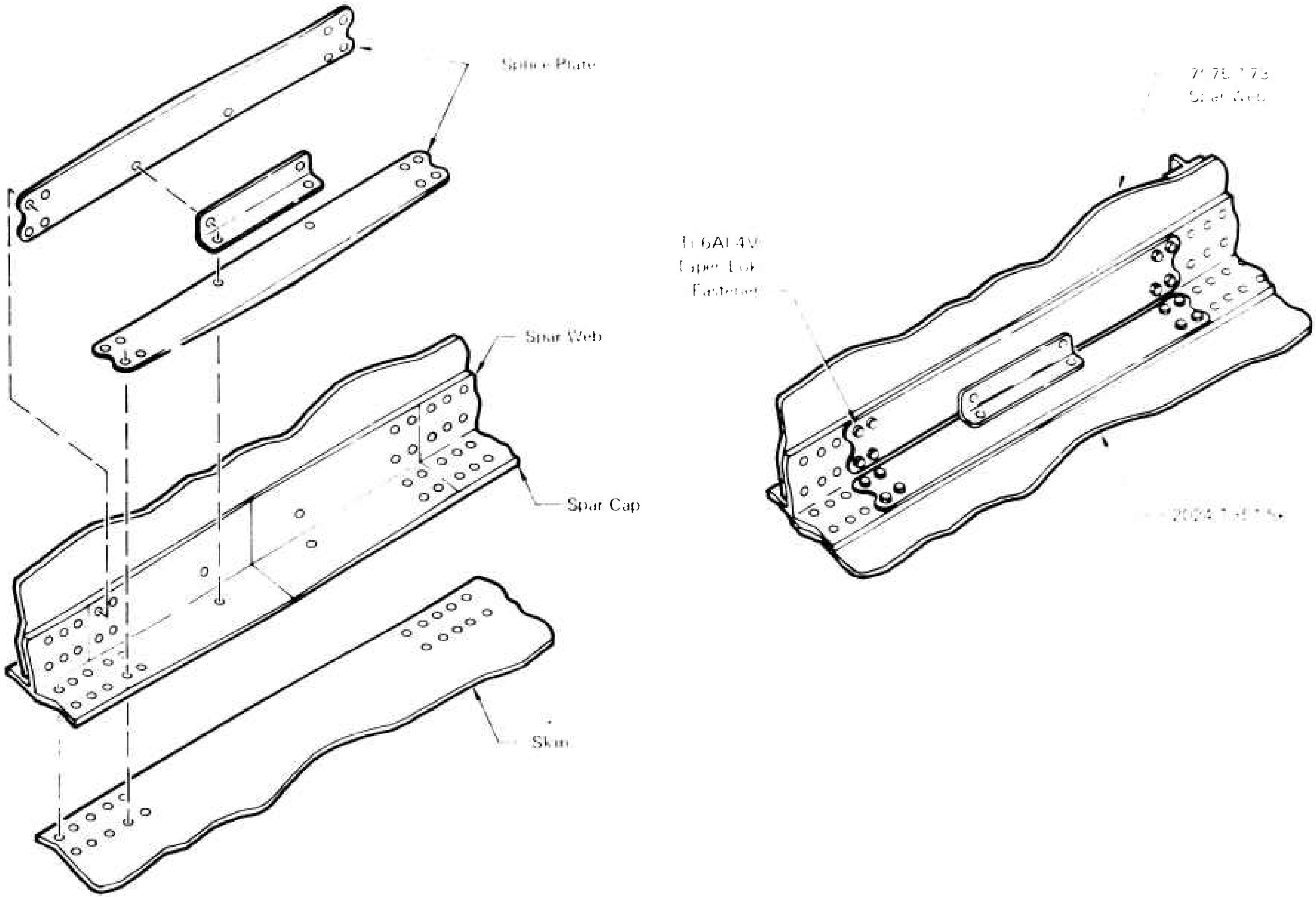


Figure 5 Typical Spar Splice Commercial Aircraft Wing

The airframe survey indicated that the parameters listed below vary significantly in aircraft usage.

- o Type of fastener in the assembly
- o Fastener material
- o Interference or clearance between fastener and structure
- o Assembly torque applied to the fastener
- o Stress level of joint
- o Cyclic load frequency of joint
- o Load transfer in the parts

These parameters influence the severity of fretting damage insofar as t. determine the relative motion between parts and load (clamp-up) between surfaces producing friction forces and fretting debris.

3.2 Fretting Specimen and Test Program Definition - The aim of Task I testing was to simulate a structural joint in a test element and to apply cyclic loading to that element to determine which conditions, if any, would cause sufficient fretting damage to reduce the fatigue resistance of titanium. This required a simple structural simulation of an actual aircraft joint in which design parameters can be varied. Attached plates on the side of a metal strip subjected to cyclic loads high enough to induce fatigue failure have been used in MCAIR development test specimens on advanced aircraft. This specimen design permits testing of a structural part (the center specimen) under a real fatigue environment along with the effect of fretting induced under the attached side plates.

Load transfer into the attached plates depends upon the variables such as fastener type, installation fit, etc., which are actual design parameters found in structural assemblies of skins, stringers, and longerons. The level of each of these parameters is based directly on the real joints surveyed. For any given set of conditions, load transfer can be varied by the length and thickness of the attached doubler plates. Since load transfer directly affects the relative motion between doubler and specimen and the severity of fretting, calculations and tests were performed to establish the dimensions required to allow "high" and "low" load transfer.

In order to determine the length and thickness of the doublers for "high" and "low" load transfer, an elastic analysis of the specimen was performed as discussed in Appendix A. These calculations predicted about 8% load transfer (per doubler) for 1 inch spacing and about 20% for 6 inch spacing. The normal design limit for a fastener in a joint is 2/3 of the shear strength. At high stress levels the amount of predicted load transfer using a doubler with 6 inch spacing closely approaches the shear strength of the fastener. Since the elastic analysis assumed zero clearance between fastener and hole, it was decided to perform static tensile tests to determine doubler loads.

As shown in Figure 6, strain gauges were attached to the doubler plate on the static tensile specimens. Readings were taken at 5,000 lb increments as the gross load transferred through the fasteners and doubler was calculated from the strain gauge readings. Hi-Lok fasteners were used in static testing. At 35,000 lb load, load transfer per doubler was 113 lb (.3%) for 1-inch spacing and 3,000 lb (8.6%) for 6-inch spacing. Doubler thickness was held constant at 0.25 inch. As anticipated, the test results produced lower load transfer than predicted by the elastic analysis due to the assumption of zero clearance between fastener and hole in the elastic analysis. In order to limit static testing, and knowing additional changes could be made after fabricating the fatigue specimens, it was decided to continue with 1 inch and 6 inch fastener spacings based upon these test results.

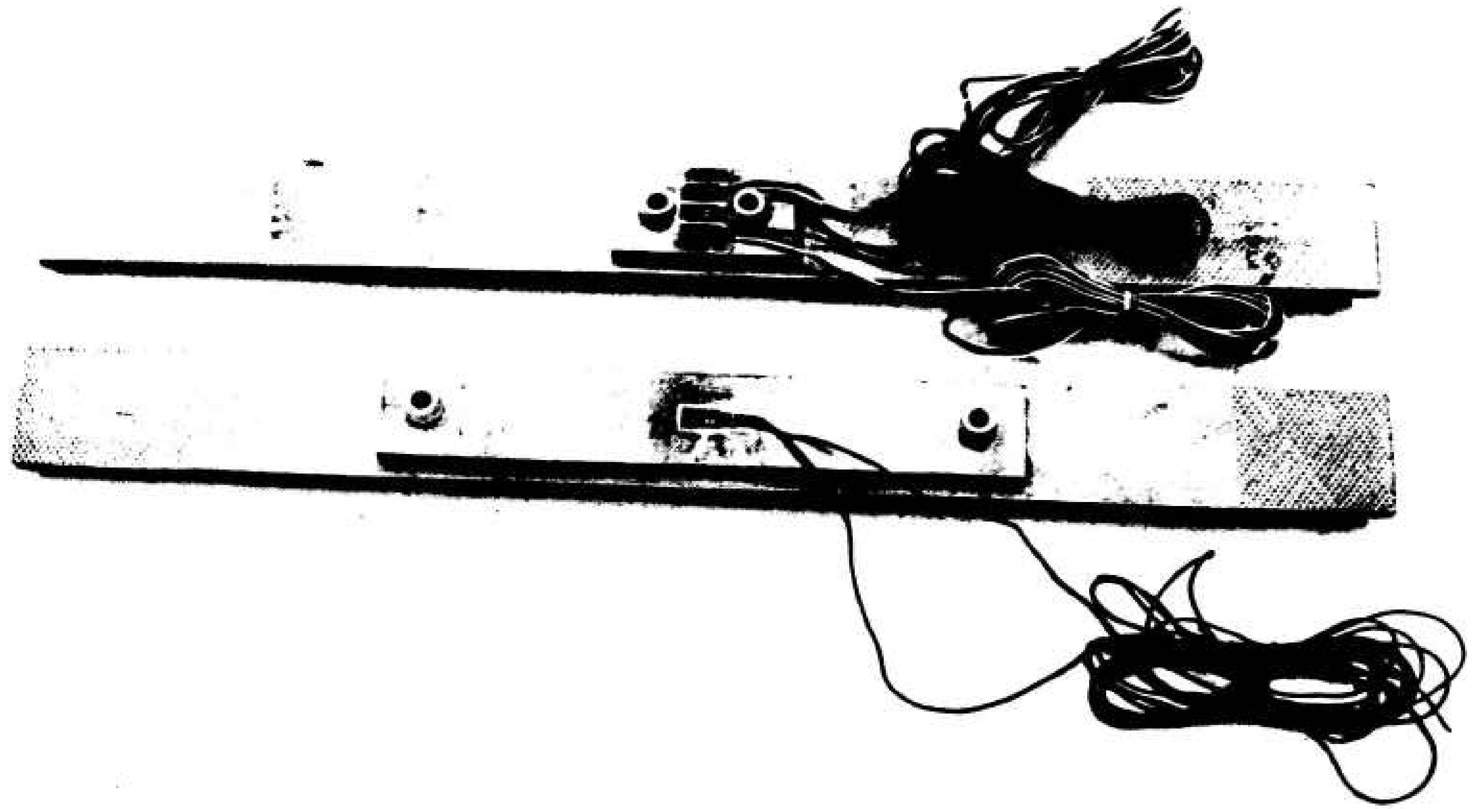
Figure 7 describes the original specimen design for Task I. Other than the width and thickness of the doublers and specimen at the gauge section, the choice of overall specimen length, shape, etc. were predicated on the fixturing requirements of the Sonntag fatigue testing machine to be used. In order to assemble specimens in the testing machine, rather large clearance was required between the loading hole and pin. Because of the very high stress concentration at the loading hole, fretting failures occurred at the loading hole in some of the Task I test specimens. To insure against fretting fatigue failure at the loading hole in Task III, interference fit steel bushings were fitted into the loading holes.

The detailed test plan for Task I is shown in Table II. The plan was designed to evaluate those parameters previously cited in the joint survey, i.e. fastener type, material, interference, installation torque, stress level, cyclic loading frequency and load transfer.

The type of fastener is important because different clamp-up characteristics induce varying amounts of normal pressure at the interface. Fastener material is a factor because of differences in friction at the fastener hole surface. A steel fastener, because of its higher modulus, should also effect more load transfer than a titanium fastener with less relative deflection at the faying surface. Fastener interference is also an important consideration. Interference fit increases fatigue life because of the lower effective stress concentration at the hole and the reduced relative motion of the faying surfaces.

Loading characteristics undoubtedly are significant in terms of affecting the interaction between fretting and fatigue. For example, at higher stress levels, the relative deflection is greater but the number of cycles to failure is reduced. Fewer cycles lessen the chances that fretting will contribute toward failure.

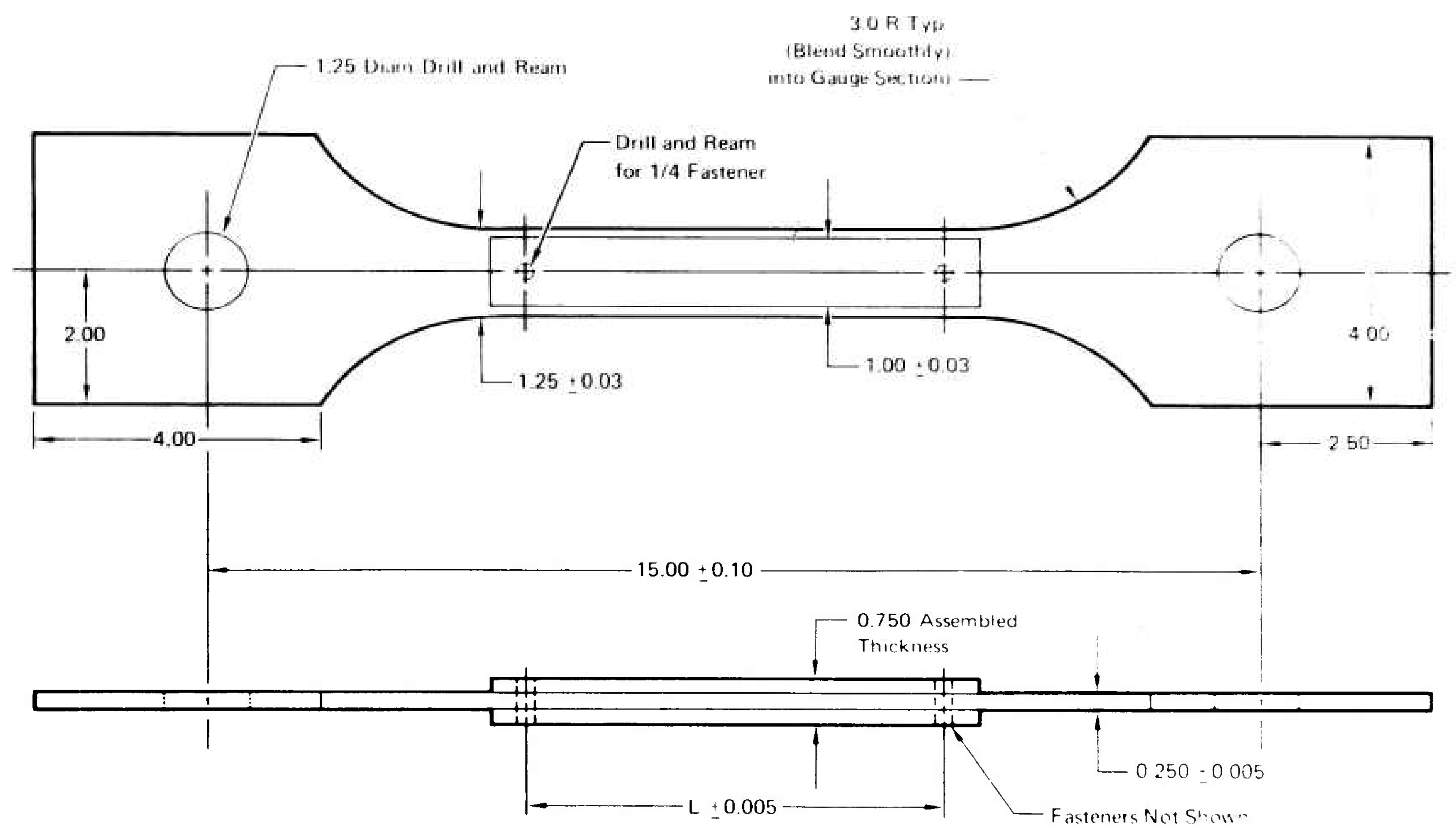
High cyclic loading frequency could possibly induce temperature effects at the interface that might aggravate the fretting condition. Although the airframe survey had shown most primary structure joints to be subject to low cyclic frequency, it was not practical to run the tests at one cycle per second. As a result, a cyclic loading frequency of 30 cps was chosen for most tests, with six to be run at 5 cps to determine the effect of cyclic loading frequency.



P_{Max} = 35,000 Lb
Doubler Load: 6 Inch Spacing = 3,000 Lb, 8.6%
1 Inch Spacing = 113 Lb, 0.3%

GP71-0879-29

Figure 6 Load Transfer Test Specimens



High Load Transfer	"L"	6.000 in.
Low Load Transfer	"L"	1.000 in.

All Dimensions are Inches

Figure 7 Original Design, Fatigue Specimen – Task I

Table II Task I Test Plan for Determining Fretting Parameters

Design Parameter	Specimen Quantity	Specimen Number	Load (1) Transfer	Fastener Type (5)	Fastener Clearance (in.)	Fastener Torque (in.-lb)	Load (2) (lb)	Frequency
a. Fastener Type	9	1-3 4-6 7-9	Low Low Low	Ti HiLok Ti-Screw Ti TaperLok	0.0005-0.0020 0.0005-0.0020 0.0035-0.0045 (3)	60 70 Pull In (4)	High High High	30 cps 30 cps 30 cps
b. Fastener Material	3	10-12	Low	Steel TaperLok	0.0035-0.0045 (3)	Pull In (4)	High	30 cps
c. Fastener Interference	3	13-15	Low	Ti-HiLok	0.0005-0.0025(3)	60	High	30 cps
d. Fastener Installation Torque	3	16-18	Low	Ti-Screw	0.0005-0.0020	10	High	30 cps
e. Stress Level	18	19-21 22-24 25-27 28-30 31-33 34-36	Low Low Low Low Low Low	Ti-HiLok Ti-Screw Ti-TaperLok Steel TaperLok Ti-HiLok Ti-Screw	0.0005-0.0020 0.0005-0.0020 0.0035-0.0045 (3) 0.0035-0.0045 (3) 0.0005-0.0025 (3) 0.0005-0.0020	60 70 Pull In (4) Pull-In (4) 60 10	Low Low Low Low Low Low	30 cps 30 cps 30 cps 30 cps 30 cps 30 cps
f. Cyclic Loading Frequency	6	37-39 40-42	Low Low	Test Conditions will Represent the Two Most Serious Fretting Conditions Found in Tests (a) through (e)				1 cps 1 cps
g. Load Transfer	6	43-48	High	Test Conditions will Represent the Two Most Serious Fretting Conditions Found in Tests (a) through (f).				

Notes:

(1) Low Load Transfer 1 inch between fasteners.
High Load Transfer 6 inches between fasteners.

(2) High Load As required for 10,000-20,000 cycles to failure.
Low Load - As required for 100,000-200,000 cycles to failure.

(3) These fasteners installed with interference fit as listed.

(4) Pull-in torque range 120 to 150 in.-lb.

(5) Ti HiLok (HL 11VV 97 8 12), Ti Screw (NAS 664 13HT)
Ti TaperLok (TLV 100-4 12 D2). Steel TaperLok (TLC100 4 12 D2)

(6) Axial tension compression loading with

$$R = \frac{(\text{Minimum Stress})}{(\text{Maximum Stress})} = 0.1.$$

High levels of shear load transfer cause high fastener bearing loads. This increases the effective stress concentration at the fastener hole and reduces the potential for fretting induced failure. Depending on the stress levels the part was expected to fail due to the higher stress concentration before fretting damage could become serious. For low load transfer, high bearing loads are not present. This decreases the stress concentration and increases the fatigue life such that fretting damage may become the main cause of failure.

3.3 <u>Specimen Fabrication</u> - Fabrication of 64 specimens from Ti-6Al-6V-2Sn plate to the design of Figure 7 was as follows:

- o Chemical mill to 0.250 ± 0.002 inch thickness
- o Saw oversize blanks
- o Mill to square up blanks
- o Drill tooling holes, 1/2 in. dia
- o N/C profile mill
- o Jig Bore loading holes
- o Deburr
- o Drill, ream, deburr fastener holes
- o Attach strain gauges
- o Assemble

Preparation of holes for Taper-Lok fasteners included:

- o Drill 15/64-inch fastener pilot hole through three piece assembly (use drill jig)
- o Drill tapered hole and countersink (use drill jig and briles TLD 2030 A2-4 drill, adjust depth for about .006 inch fastener interference).
- o Hand ream to .0039 - .0046 inch diametral interference using a Briles TLD 2060 AR-2-4 reamer.
- o Inspect each hole for 70% minimum bearing contact (use blue tooling dye on Taper-Lok pin). A typical blued pin is shown in Figure 8 after passing inspection.

GP71-0879 31

Figure 8 A Typical Blued Pin Used for Minimum Bearing Test on Holes for Taper-Lok Fasteners

The Ti-6Al-6V-2Sn plate (annealed) material was taken from Titanium Metals Corporation Heat K-4697 and analyzed:

C - .026%	H - .004%
Fe - .73%	Sn - 2.1%
N - .011%	O_2 - .16%
Al - 5.6%	C_u - .64%
V - 5.6%	

Typical mechanical properties were:

F_{t_y}	155 ksi
F_{t_u}	160 ksi
Elongation	15.5%

3.4 Task I Fatigue Testing - As evidenced in the airframe joint survey, stresses varied from 10 to 115 ksi. Only two stress levels (high and low) were selected for testing. For the high stress level, there were two criteria. One was that the high stress level should be about 100% of the design limit load. For advanced titanium airframe applications, 100% design limit stress was approximately 60 to 80 ksi. The other factor was that the stress level should give a joint life of about 10,000 cycles.

For the low stress level, a joint fatigue life of 100,000 cycles or about 10 times greater than the life obtained at the high stress level was the criterion. This order of magnitude increase simulated the number of cycles at low stress found during the airframe joint survey.

Six preliminary fatigue specimens were tested on the Sonntag SF-10-U fatigue machine fitted with a 5 to 1 load multiplying device and an automatic stop fixture to prevent damage to the fractured surfaces (see Figure 9). Based on the results of testing these six specimens, "low" load was set at 12,000 lb (38,400 psi gross stress) and "high" load was set at 22,000 lb (70,400 psi gross stress). The complete data for the six preliminary specimens (No's A through F) and the remainder of Task I testing is listed in Appendix B.

Results of Task I - Interpretation of the results and of the fractured specimens was based on the location of the failure origin. Fracture originated either at fretting damage between the faying surfaces, or at the high stress concentration points in the fastener holes. The point of fracture origin was determined by examining the fracture surfaces at low magnification (10-25X). Figures 10 and 11 show typical failure origins.

The fractured surfaces of each fatigue failed specimen were analyzed. Although multiple fracture origins were observed on many of the specimens, only two had origins at both the faying surface and at a fastener hole. (See Appendix C, Specimens 5 and 24.) In these latter two cases neither origin could be confidently established as the primary origin. All other fractures originated either "at surface fretting damage" or "at the fastener hole."

Those specimens with surface fretting damage as the failure origin were examined with the scanning electron microscope (SEM). Figures 12 and 13 show typical fretted surfaces at two magnifications. No detectable differences were observed between fretted surfaces resulting from different joint parameters. Figure 14 is a SEM photo of an unfretted surface.

Table III lists by study parameter the average cycles to failure of the specimens tested. (See Appendix B for complete data listing by specimen and for fretting origin locations.) Specimens 1 through 36 (Groups a through e) in Table III were designed to select, at low load transfer, the conditions which cause fretting damage sufficient for fatigue failure. Under these conditions fracture origins indicating fretting fatigue failure were found on:

- Titanium Taper-Lok fastened joints at high and low stress.
- Steel Taper-Lok fastened joints at high and low stress.
- Titanium Hi-Lok fastened joints at low stress.

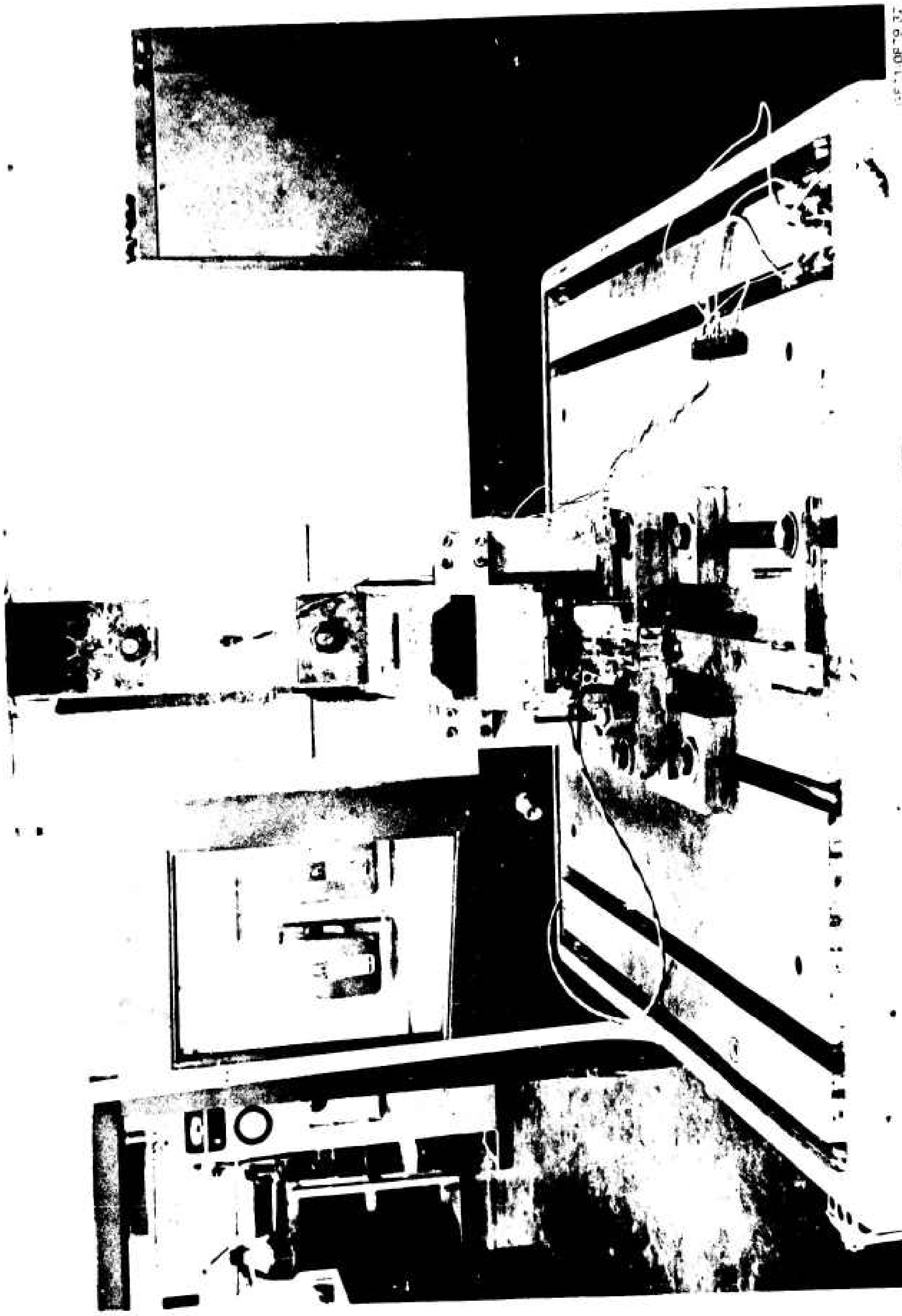
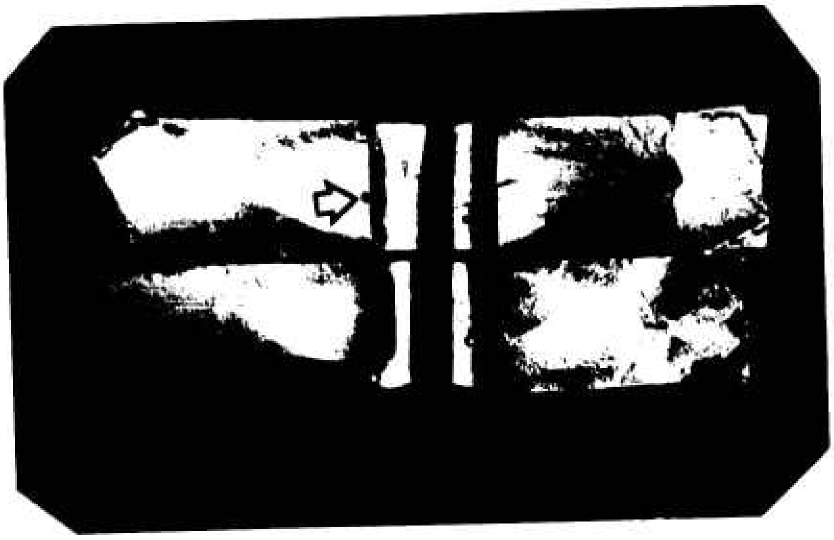
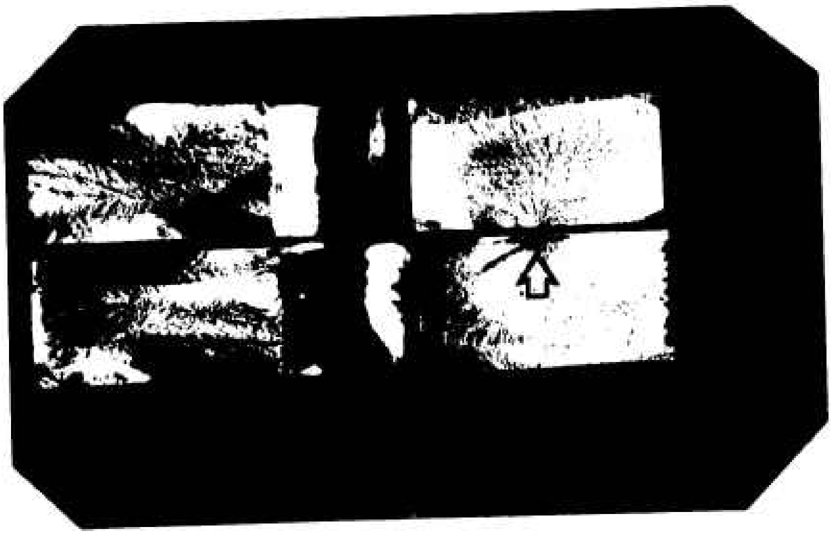


Figure 9 Test Assembly for Tasks I and III



GP71-0879-33

Figure 10 Typical Fracture Origin at Fastener Hole



GP71-0879-34

Figure 11 Typical Fracture Origin at Surface Fretting Damage

Figure 12 Typical Fretted
Surface SEM Photo 300X

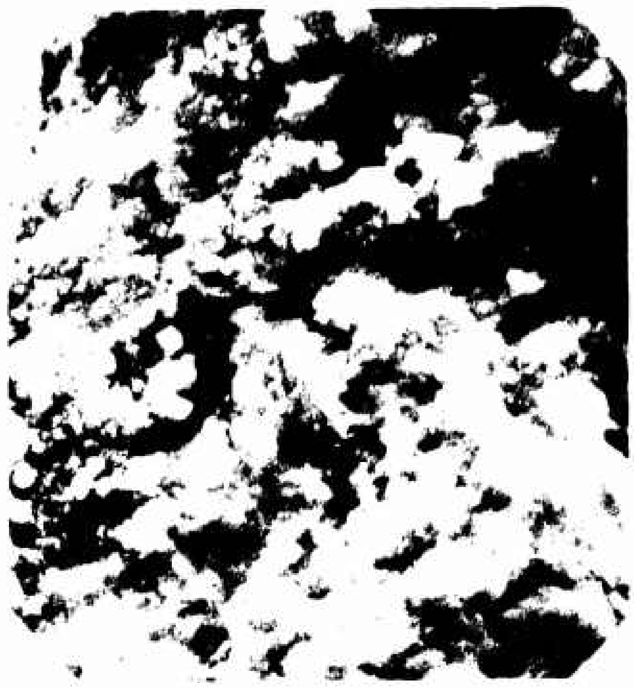
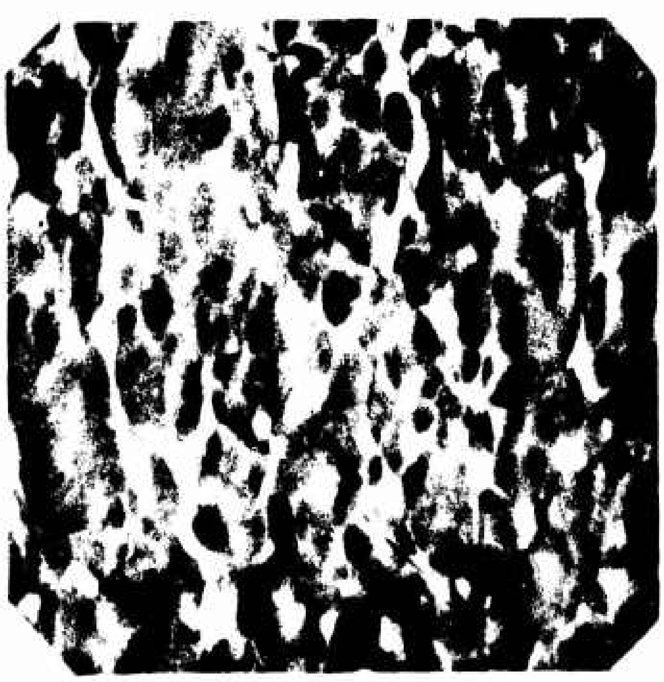


Figure 13 Typical Fretted
Surface SEM Photo 3000X



GP71-0879-35

Figure 14 Typical Specimen Surface,
Free of Fretting Damage SEM Photo 3000X

Table III Summary Results of Task I

Study Parameter		Cycles to Failure, Gross Stress Level: 70.4 ksi	38.4 ksi
		a.	e.
Fastener Type	Hi Lok (Ti)	12,100	(237,000)
	Screw (Ti)	10,750	112,000
	Taper Lok (Ti)	(70,500)	(270,000)
		b.	
Fastener Material	Taper Lok (Ti)	(70,500)	(270,000)
	Taper Lok (Steel)	(88,300)	(295,000)
		c.	
Fastener Fit (Hi Lok)	Clearance $\left(\frac{.0005}{.0015}\right)$	12,100	(237,000)
	Interference $\left(\frac{.001}{.002}\right)$	11,700	119,000
		d.	
Fastener Torque (Screw)	Normal (70 in. lb)	10,750	112,000
	Low (10 in.-lb)	6,180	61,700
		f.	
Frequency (Ti Taper-Lok)	High (30 cps)	(70,500)	(270,000)
	Low (5 cps)	(65,000)	(340,000)
		g.	
Load Transfer (Ti Taper-Lok)	Low (2 in. Doubler)	(70,500)	(270,000)
	High (7 in. Doubler)	—	(248,000)
Load Transfer (Steel Taper Lok)	Low (2 in. Doubler)	(88,300)	(295,000)
	High (7 in. Doubler)	–	(297,000)

Notes:

(1) Taper-Loks installed $\frac{0.0039 \text{ in.}}{0.0046 \text{ in.}}$ interference; screws installed $\frac{0.0005 \text{ in.}}{0.0015 \text{ in.}}$ clearance.

(2) Entries in parentheses indicate fracture originated at surface fretting damage.

(3) Each entry is a logarithmic average of individual data.

GP71 0879 20

Fracture originated at fretting damage between faying surfaces on all specimens with Taper-Loks at low stress levels. Therefore, these conditions were judged most likely to produce fretting fatigue and were used in the low frequency and high load transfer tests. A frequency of 5 cycles per second was used in the low cyclic frequency fatigue tests. The cycles to failure for these last two parameters (groups f and g) did not differ significantly from those of groups a through e. Thus, it is concluded that low frequency and high load transfer as tested in this program are not any more conducive to fretting initiated fracture than high frequency and low load transfer.

Finally, control specimens were tested using those parameters causing fretting damage, except that strips of Nylatron GS (MoS_2 filled nylon) were placed between the central member and doublers. This procedure prevented fretting surface damage from occurring, giving a joint fatigue life without fretting on the faying surfaces.

The control specimens (No.'s 49, 50, and 51-2) all had fatigue lives in excess of those specimens where fretting occurred. Specimen 49 lasted over 600,000 cycles which was considerably longer than any previously tested specimen. The fracture did not originate between the faying surfaces, but its exact origin in the fastener hole was uncertain. Fatigue testing was stopped on specimen 50 at 2,500,000 cycles with no failure. Specimen 51 failed at the loading hole in the gripping fixture and was inconclusive for control data use. Specimen 51-2 failed at 5,314,000 cycles in the gripping fixture and entirely out of the gauge section. The effect of fretting damage on fatigue life is clearly observed now, since joints with and without fretting damage between the faying surfaces can be compared.

- Group a data (Table III) compares the three fastener types at 70.4 ksi stress. There was no significant difference between cycles to failure of specimens with Hi-Loks or screws. Both were installed in .0005-.0015 inch clearance holes. Taper-Lok fastened specimens lasted about six times longer than those with screws and Hi-Loks. Only the Taper-Loks ran long enough for surface fretting to initiate fracture.

- Group b data compares A-286 steel alloy Taper-Loks to Ti-6Al-4V alloy Taper-Loks. All of the fractures in this group originated at surface fretting damage. The difference between the cycles to failure for the two alloys is not significant although the titanium fastened specimens failed somewhat earlier. Since most titanium structures use titanium alloy fasteners, the latter were preferred for Task III testing.

- Group c data shows the difference in fatigue life of specimens assembled with Hi-Lok fasteners in clearance (.005-.0015 inch) and in interference (.001-.002 inch) holes. The interference fit shows no advantage in improving fatigue and at low stress is considerably lower lived than the clearance hole. Interference was achieved by driving the straight shanked Hi-Lok fasteners into the holes. The relatively high driving force required and the lack of improved fatigue life suggest that damage to the surface of the fastener hole may have caused fatigue critical stress risers.

- Group d data compares normal (70 inch-pounds) and low (10 inch-pounds) installation torques on a screw fastener. As expected, the low torque fastened specimens failed early due to the lower clamp-up. At low torque, very little of the load transferred into the doubler plates is due to friction between the parts; proportionately more of the transferred load is carried through the fasteners. The added bearing load at the fasteners increases the stress concentration and contributes to earlier failure.

  Since none of these specimens failed because of surface fretting, these parameters were not considered for further test in Groups f and g.

- Group e data compares the effect of stress level at each set of conditions. While higher stress will cause earlier failure, it is not certain that given parameters will cause failure due to surface fretting damage at either high or low stress. For a given set of conditions, a critical number of fatigue cycles must pass for fretting damage to develop to the point of starting fracture. If conditions, high stress for example, lead to failure before this critical number of cycles is passed, the fracture will not originate from fretting damage. Since Taper-Lok fasteners can increase the fatigue life at stress concentrated holes several fold, they can be associated more frequently with fretting-fatigue failures.

- Group f data is the result of tests comparing high and low cyclic loading frequencies. These specimens were assembled with Ti-6Al-4V Taper-Loks and tested at 5 cycles per second under high and low stress levels. There is no significant difference in the data at the frequencies (5 and 30 cps) tested. All the specimens tested had fracture origins at fretting damage between the faying surfaces.

- Group g data compares the effect of high and low load transfer. Strain gauge measurements during tests ranged 1.2%-12.5% (per doubler) with short doublers and averaged 23% (per doubler) with the long doublers. The difference between the early static tests and this data is due to the necessarily limited early testing and because Hi-Lok fasteners were used previously. Actual specimen tests, particularly with Taper-Lok fasteners, gave varying results. Because of the high load transfer (23%) measured with the 7 inch doubler, it became impossible to run these specimens at high stress level. Load transfer through the fastener would be very near the shear strength of the fasteners. One specimen (No. 46) was tested at high stress but the fastener and the specimen both failed, making the failure mechanism uncertain. Further tests at high stress would have required specimen redesign and retesting several other parameters for adequate comparison. A series of high load transfer specimens was tested at low stress level. Fretting fatigue failures were obtained; however, from the data it was concluded that high load transfer is not more conducive to fretting fatigue than low load transfer.

The conditions most conducive to fretting fatigue failure as tested in Task I are:

- Taper-Lok fasteners (normal installation)
- Low load transfer (2-inch doublers)
- Low gross stress level (38.4 ksi)
- High frequency (30 cps)

These conditions were selected for Task III specimens. Although there was no significant difference between steel and titanium Taper-Loks in the fatigue tests, Ti-6Al-4V was selected for the fasteners in Task III since it is preferred in most titanium airframe applications. There was no significant difference between the data obtained at high (30 cps) and low (5 cps) frequency. In order to shorten the duration of testing and best utilize the test equipment, 30 cps was selected for Task III tests.

4.0 SELECTION OF COATINGS, TASK II

The purpose of Task II was to select coatings to be tested in Task III. This task consisted of a survey of existing knowledge of titanium coatings, screening and mechanical properties tests on candidate coatings, and the final selection of three coating systems for subsequent fretting-fatigue tests.

4.1 Coatings Survey - This survey covered commercially available processes, published reports, McDonnell Douglas investigations and private communications (see Appendix D for individual data sheets and references). Coatings/surface treatments for titanium were broken down into six categories:

- o Chemical surface coatings
- o Lubricant coatings
- o Plated coatings
- o Vapor deposits
- o Diffusion layers
- o Sprayed (metallized) coatings

Chemical Coatings - This group includes those chemical treatments which convert the titanium surface to a different compound and those processes in which electrolysis is used to anodically form a compound on the surface. In general, this class of coatings has the following advantages.

- o Process equipment is of the type commonly used for other aqueous coating solutions and is available.
- o Racking methods are generally simple so that handling is minimized.
- o Costs are moderate and can be expected to be similar to chemical coating facilities for aluminum.

Characteristics of these coatings are:

- o Thin coatings, generally less than 0.0005 inch.
- o Rather poor wear resistance when used as coated.
- o Good adherence.

Numerous solutions have been studied in an attempt to produce a tightly adherent coating on titanium. Many different baths, containing phosphates and fluorides for simple immersion treatment, and acidic and alkaline solutions for anodic treatment, can be found in the literature. While their purposes vary (decorative, corrosion resistance, bond coats for lubricants, hardcoat) they universally do not compare to the tenacity and durability of aluminum conversion coatings to which they are sometimes compared.

Some of these coatings produced on titanium are covered by a somewhat loosely adhering surface film that must be removed. Appendix D includes data sheets on coatings of this type.

Wear tests at MCAIR have shown that only light loads can be tolerated. Hardness is rather low. There are mixed reports on the general effect of conversion coatings on mechanical and fatigue properties of the titanium alloys. In general, there is a slight decrease of fatigue life of the base metal when coated. These coatings are recommended for use only as a bond coat for solid film lubricants.

For this program, the following coatings were selected:

- Ti-Cote VII (Electrofilms Inc.)
- Tiodize II (Tiodize Co.)
- MCAIR Anodize
- Fluoride Phosphate Conversion Coating

Solid Film Lubricant - This group of coatings depends on the natural lubricity of materials such as molybdenum disulfide, graphite and Teflon to reduce friction and alleviate wear between surfaces. They are contained in various binders that allow them to be applied to the parts. The characteristics of the binder and of various additives to the basic pigment are used in specific applications such as high temperature, high pressure, air cure, etc. Lubricants on untreated surfaces have a tendency to be removed or wiped away under bearing loads. Consequently, these coatings are applied only after the surface has been grit blasted or chemically treated.

Considering its superior lubricating properties at room temperature, Molykote 106 (MoS_2) was selected for evaluation as well as the Air Force developed coating AFSL-41. Teflon coatings were also selected.

Plated Coatings - Plating processes in aqueous solutions are comparable in cost to anodizing. Historically, plating on titanium has been plagued by the tendency of a freshly activated surface to instantly reform an oxide layer on which it is nearly impossible to get a tightly adherent deposit. Many investigators have reported approaches to overcome this problem. MCAIR has tested many of these processes by bending a thin plated coupon 180° until it fractures. An adherent plate must not flake or chip from the basis metal at the fracture. MCAIR has developed a process for nickel plating titanium alloys that has consistently passed this test. Of the many plating processes investigated, nearly all use some type of post-plate heating to achieve a bond. There is no known process capable of consistently plating an adherent deposit without using a post-plate diffusion baking procedure.

Practically every common metal has been investigated in attempts to electrolytically plate on titanium alloys. These studies have been aimed at as many different objectives as have the chemical conversion coatings. In particular, many metals have been studied as intermediate plates to be used as a bond coat for another metal with more desirable qualities. Cadmium, copper, cobalt, chromium, gold, iron, nickel, silver, tin and zinc efforts can all be found in the literature. Appendix D lists a few of these references. Based on their adhesion demonstrated in previous tests, the following were selected for evaluation:

- o MCAIR nickel process
- o Electroless nickel, General American Transportation Company

Vapor Deposits - There are three basic methods of applying vapor deposits. The first and most common physical vapor deposition (PVD), involves vaporizing the coating material to be deposited in a vacuum. Condensation occurs when the vapor contacts the surface of the part to be coated. Ion vapor deposition (IVD) is similar except an electrical potential is applied between the coating source and the substrate. This in effect ionizes the coating vapor and accelerates it toward the substrate, providing better adhesion. Chemical vapor deposition (CVD) consists of passing vaporized organometallics over a heated substrate. The heat breaks down the vapor compound and leaves a metallic deposit.

MCAIR has achieved ductile and adherent metal coatings using all three of the vapor phase techniques. Each has its unique advantages and disadvantages. IVD was selected for testing on this program because of its consistent and exceptionally good coating to substrate adhesion.

Aluminum IVD coatings were chosen. Aluminum is of particular interest because of its versatility. Recent tests have shown that IVD aluminum on titanium substrates can be subsequently anodized by conventional techniques used for aluminum alloys. This suggests that the final coating can be "tailored" to meet the particular fretting parameters which result from various design requirements.

Diffusion Coatings - This category includes the various high temperature processes that diffuse atoms of a hardening element into the titanium surface at an elevated temperature.

The source of the diffusing material may be liquid salt, gas or solid. Boron, carbon, nitrogen, aluminum, chromium and other elements have all been studied by many investigators (see data sheet references). All of these processes use special equipment and have a high cost. However, because of the high processing temperatures, coating thinness, and possible embrittlement of the basis metal, these coatings were not included in this program.

Sprayed (Metallized) Coatings - "Metallized" coatings are produced by melting metallic or ceramic materials and atomizing them as they are sprayed under gas pressure. The three basic types are distinguished by their source of heat:

- o Oxy-acetylene (popularly called "flame-spraying")
- o Plasma gun
- o Detonation gun

The equipment increases in expense and sophistication in the same order. All of the coatings are inherently porous and brittle. Although "fusible" coatings do exist, the coatings considered for titanium are solidified at about the time they strike the part and it is generally not possible to identify a metallurgical diffusion bond zone. Bond strength is due to mechanical keying of the deposit into micro fissures on the surface. The higher spray velocities do increase the bond strength, however, these coatings have little ductility and will not adhere when a thin coated strip is bent flat on a small radius.

The three processes can be compared as follows:

	Porosity	Velocity	Bond	Cost
O_2-C_2H_2 flame	High	500 ft/sec	Fair	Moderate
Plasma flame	Lower	1500 ft/sec	Better	Higher
D-Gun	Much lower	2500 ft/sec	Best	Highest

All three methods generally require grit blasting of the surface prior to coating to improve adhesion.

For this program, plasma sprayed bronze, copper-nickel-indium and tungsten carbide and detonation gun sprayed tungsten carbide were investigated. All of these materials give excellent wear surfaces, however, their effect on fatigue properties of titanium requires investigation.

Shot Peening - This surface treatment is recognized for its ability to improve a part's resistance to fatigue. Various investigators have also studied the feasibility of reducing fretting damage by shot peening. Some of these studies have reported reduced fretting wear in highly loaded tests. These tests, as well as wear tests at MCAIR, have shown that shot peening alone is not the complete solution to fretting damage. However, shot peening was selected as a pretreatment prior to applying the coatings mentioned above where fatigue reduction is an inherent characteristic of the coating.

4.2 Screening Tests - Test strips (Ti-6Al-6V-2Sn alloy, .032" x 1" x 4") were coated with each of the 11 coatings shown in Table IV. (In addition to these 11 and the two variations of electroless nickel, test strips were also coated with Teflon, Molykote 106, and AFSL-41 solid film lubricant.) Each coating was examined for appearance and uniformity; tested for adhesion by scraping with a knife blade; tested for adhesion by bending; sectioned and examined microscopically for bond, density, and general structure. The hydrogen content of the basis metal was determined as another portion of the screening sequence. From this screening, eight coatings were selected for fatigue and tensile tests. In addition to the coatings, the surface treatment of shot peening and grit blasting was tested and as-machined control specimens were tested for comparison.

The results of screening tests are shown in Table IV. Adherence of the coating, a primary concern, ideally should be sufficient to prevent flaking or lifting of the coating when the basis metal is bent until fractured. Flame-sprayed coatings are primarily mechanically bonded to the substrate, and in many cases, are more brittle than the chemical deposits and electroplates. These coatings typically will not pass the above bend test. Their adherence was tested by bending the test strips around a 1/2 inch diameter mandrel. The knife scratch test was used on some deposits as a very rough comparison of hardness. The other coatings, electroless nickel and tungsten carbide, are obviously hard surfaces. The hydrogen content (per ASTM Procedure E-146) of Ti-6Al-6V-2Sn after coating was within the acceptable level.

Table IV Task II Screening Test Results

Coating	Bend to Break		1/2 in. Diam. Mandrel		Knife Test		Comments	Hydrogen Content* (ppm)
	Outside Bend	Inside Bend	Outside Bend	Inside Bend	Bond	Hardness		
1) "Tiodize" II	Pass	Pass			Pass	Low	Matte Surface	69
2) MCAIR Anodize	Pass	Pass			Pass	Low	Smooth Surface	
3) "Ti Cote" VII	Pass	Pass	–	–	Pass	Low	Dull Surface	114
4) Fluoride Phosphate	Pass	Pass	–	–	Pass	Low	Matte Surface	80
5) Electroless Nickel a.	Pass	Pass	–	–	Pass	High	Bright ($550^{o}F$ - 1 hr)	81
b.	Pass	Pass	–	–	Pass	High	Straw Color ($550^{o}F$ - 15 hr)	–
c.	Pass	Pass	–	–	Pass	High	Blue Color ($750^{o}F$ - 1 hr)	–
6) MCAIR Nickel	Pass	Pass	–	–	Pass	Medium	Bright	58
7) Detonation Gun Spray Tungsten Carbide	Pass	Fail	Pass	Fail	Pass	High	–	58
8) Plasma Spray Copper-Nickel-Indium	Pass	Pass	Pass	Pass	Pass	Medium	Excellent Bond	82
9) Plasma Spray Aluminum Bronze	–	–	Fail	Pass	Pass	Medium	–	88
10) Plasma Spray Tungsten Carbide	Fail	–	Pass	Fail	Pass	High	–	85
11) Hard Coated IVD Aluminum	Pass	Pass	–	–	Pass	High	–	51

*Hydrogen content before coating was analyzed to 40 ppm.

GP71-0879-24

Because of the limited scope of the program, only one anodic coating could be selected for further evaluation. The three anodic coatings were extremely similar and the selection of Tiodize II for further testing was based on its slightly matte surface, although it would have been desirable to test all three. These coatings were intended to be used with solid film lubricant and the matte surface of the Tiodize II appeared to be a better bonding surface. All three were coated over a previously shot peened and lightly grit blasted surface. Film thicknesses were less than .5 mil.

The electroless nickel plating was performed by General American Transportation Co., and three heat treatments were provided to enhance adherence while developing plate hardness. The 550°F-one hour treatment was chosen since it was expected to have the least effect on fatigue properties. Plate thickness was .5 mil.

The fluoride-phosphate coating was deposited in MCAIR laboratories from an aqueous bath (50 gm/L tribasic sodium phosphate, 20 gm/L potassium fluoride, 12 ml/L hydrofluoric acid, 185°F). This solution with several modifications has been reported in various places as referenced in Appendix D.

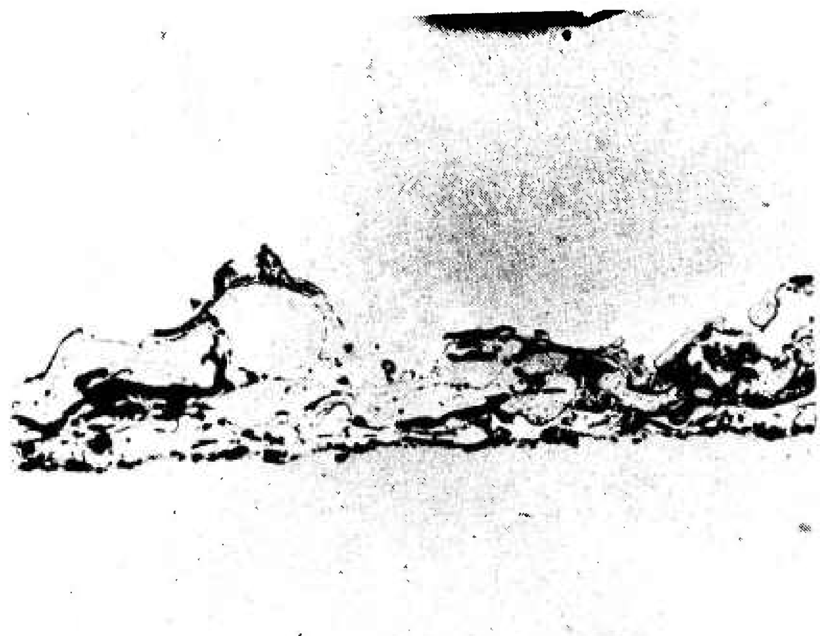
The MCAIR nickel plating procedure has been developed using a sulfamate bath. The deposit is ductile and is subjected to a short heat treatment to enhance adherence. Plate thickness was .5 mil.

All of the sprayed deposits were 3.0-5.0 mils thick. Each was shot peened and grit blasted prior to spraying except for coating 7, which was only shot-peened prior to detonation gun spraying. Coating 7 was provided by Union Carbide Corporation (LW-1N40, 85% tungsten carbide - 15% cobalt). The three plasma coatings were applied by St. Louis Metallizing Company using Metco Powder No. 58 (36.5% nickel-5.0% indium-balance copper), Metco Powder No. 51 (1.0% iron-9.5% aluminum-balance copper), and Metco Powder No. 439 (50% tungsten carbide in a self-fluxing Nichrome matrix). The ability of the Cu-Ni-In coating to pass the severe "bend-to-break" adhesion test was surprising. This coating and aluminum bronze were selected for further testing. Figures 15 and 16 compare the microstructures of the detonation gun and plasma sprayed tungsten carbides. Because of the greater density of the former, it was selected for fatigue and tensile testing.

Ion vapor deposited aluminum was coated in the MCAIR laboratory 2.0 mils thick, then hard anodized. This deposit was selected for more testing because of its good potential wear surface.

In addition to the above coatings, FEP teflon was investigated as a potential deposit over one of the conversion coatings. Although very flexible and having high natural lubricity, it was not considered further because of its tendency to extrude under pressure. Two solid lubricants were likewise compared. Molykote 106 is composed of MoS_2 in an epoxy resin and has adequate adhesion on titanium. A lubricant, AFSL-41, developed at the Air Force Materials Laboratory, was tested. The lubricants were compared by immersion in engine oils. AFSL-41 showed the poor oil resistance typical of silicone resins and was dropped in favor of the epoxy resin.

Figure 15   Detonation Gun Sprayed Tungsten Carbide, 250X



GP71-0879-36

Figure 16   Plasma Gun Sprayed Tungsten Carbide, 250X

4.3 Tensile Effect - The tensile results of coated test bars are listed in Table V. Tensile bars, to the design of Figure 17, were machined from Ti-6Al-6V-2Sn annealed 3/4 in. diameter bar. The test was conducted at a strain rate of 0.005 in/in/min. to 0.2 percent offset yield. When the yield point was reached, the strain rate was increased to produce failure within one minute. All the specimens except those detonation gun-sprayed, were steel shot-peened prior to coating to an intensity equivalent to .015 A and then lightly grit blasted with 150 mesh aluminum oxide grit. The detonation gun sprayed specimens were glass bead peened by the vendor to an intensity of .009 N prior to coating. The variations in tensile properties are not considered deleterious to the use of any of these coatings in an airframe structure. All of the flame-spraying processes heat the substrate and require auxiliary cooling to prevent overheating. The lower values for the plasma sprayed specimens may indicate need for more auxiliary cooling. In addition, the material deposited is porous and lower in tensile strength than the titanium alloy.

4.4 Fatigue Effect - The fatigue test results are shown in Figure 18. Fatigue specimens, to the design of Figure 19 were machined from the same material as the previous tensile bars (Harvey Aluminum Co. Heat No. A1-01). This material analyzed:

Al - 5.52%	V - 5.58%	H - .010%	C - .035%
Sn - 1.96%	Cu - .59%	N - .008%	Fe - .72%

For comparative testing at one stress level, 120,000 psi maximum stress was chosen because it produced fracture in control specimens in a reasonable number of cycles. All fatigue tests were in axial tension, at 30 cycles per second, using a ratio of maximum stress to minimum stress equal to +0.1. Since airframe design allowables will be lower than this, tests at one or more lower stress levels should be performed in a more extensive program. At lower stresses, the cycles to failure of the flame-sprayed and plated coatings should more closely approach the control specimen than they did here. The fatigue specimens were coated exactly the same as the tensile specimens.

At 120,000 psi, only the fluoride-phosphate and the anodize (Tiodize II) coatings lasted nearly as long as the control specimen. These coatings were the only ones fatigue tested that did not initiate fracture. As seen in Figure 20, the failure originated internally. Figure 21 shows a fracture typical of the other coatings in which multiple origins can be seen in the coating itself.

Based on the Task II effort, three treatments were chosen for Task III evaluations:

- Shot peen, grit blast, Molykote 106 solid film lubricant
- Shot peen, grit blast, fluoride-phosphate coat, Molykote 106 solid film lubricant
- Shot peen, grit blast, anodize (Tiodize II), Molykote 106 solid film lubricant

Table V Tensile Properties of Coated Specimens

Specimen Description	F_{ty} (ksi)	F_{tu} (ksi)	% Elongation
Copper-Nickel Indium, Plasma Sprayed (4.0 mils thick)	143	151	17.6
Aluminum Bronze, Plasma Sprayed (4.0 mils Thick)	144	153	17.8
Fluoride Phosphate Conversion Coating (<0.5 mil Thick)	149	159	19.0
IVD Aluminum, Hard Anodized (2.0 mils Thick)	151	159	16.8
Tungsten Carbide, Detonation Gun Sprayed (4.0 mils Thick)	153	158	16.8
Anodized, "Tiodize II" (<0.5 mil Thick)	152	160	18.0
Electroless Nickel (0.5 mil Thick)	152	160	16.3
Shot-Peened, Grit Blasted	149	160	18.1
Control, As-Machined	150	154	19.3

Note: All entries are based on the as-coated diameter and are the averages of 3 individual tests.

GP71 0879 43

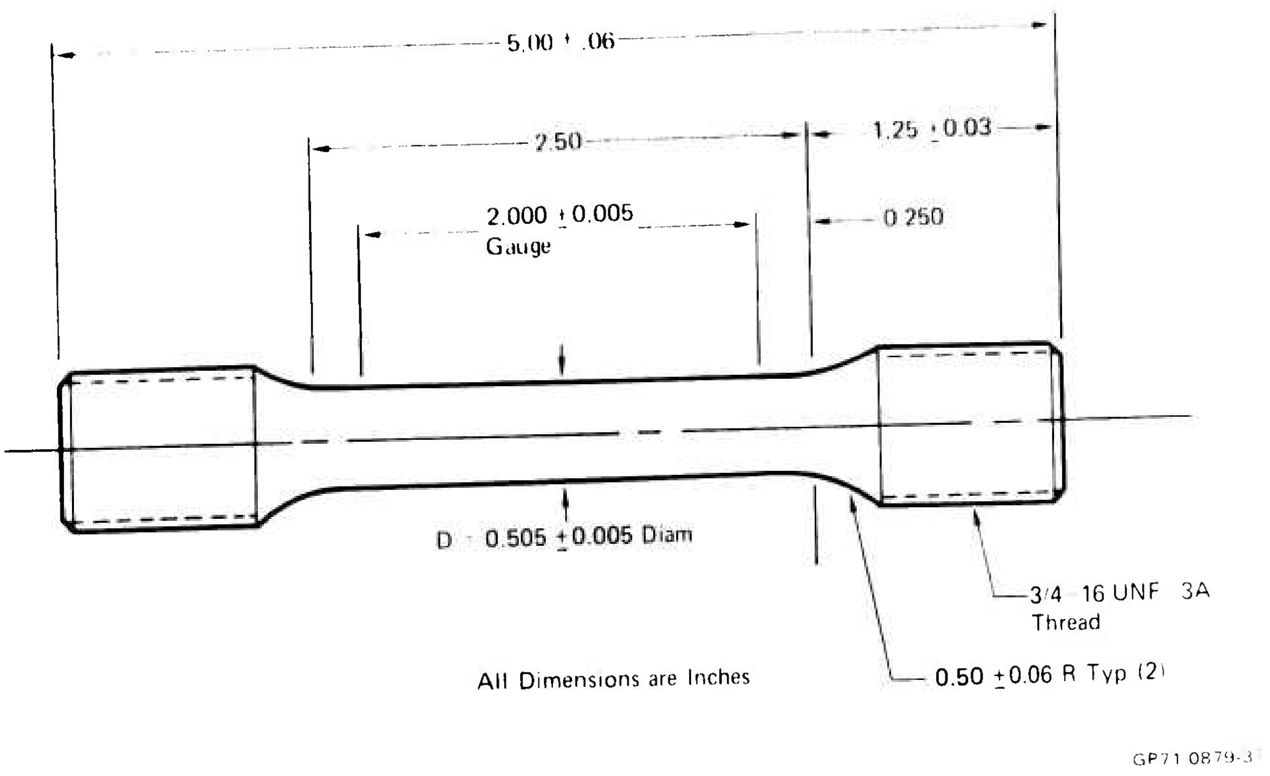


Figure 17 Tensile Specimen - Task II

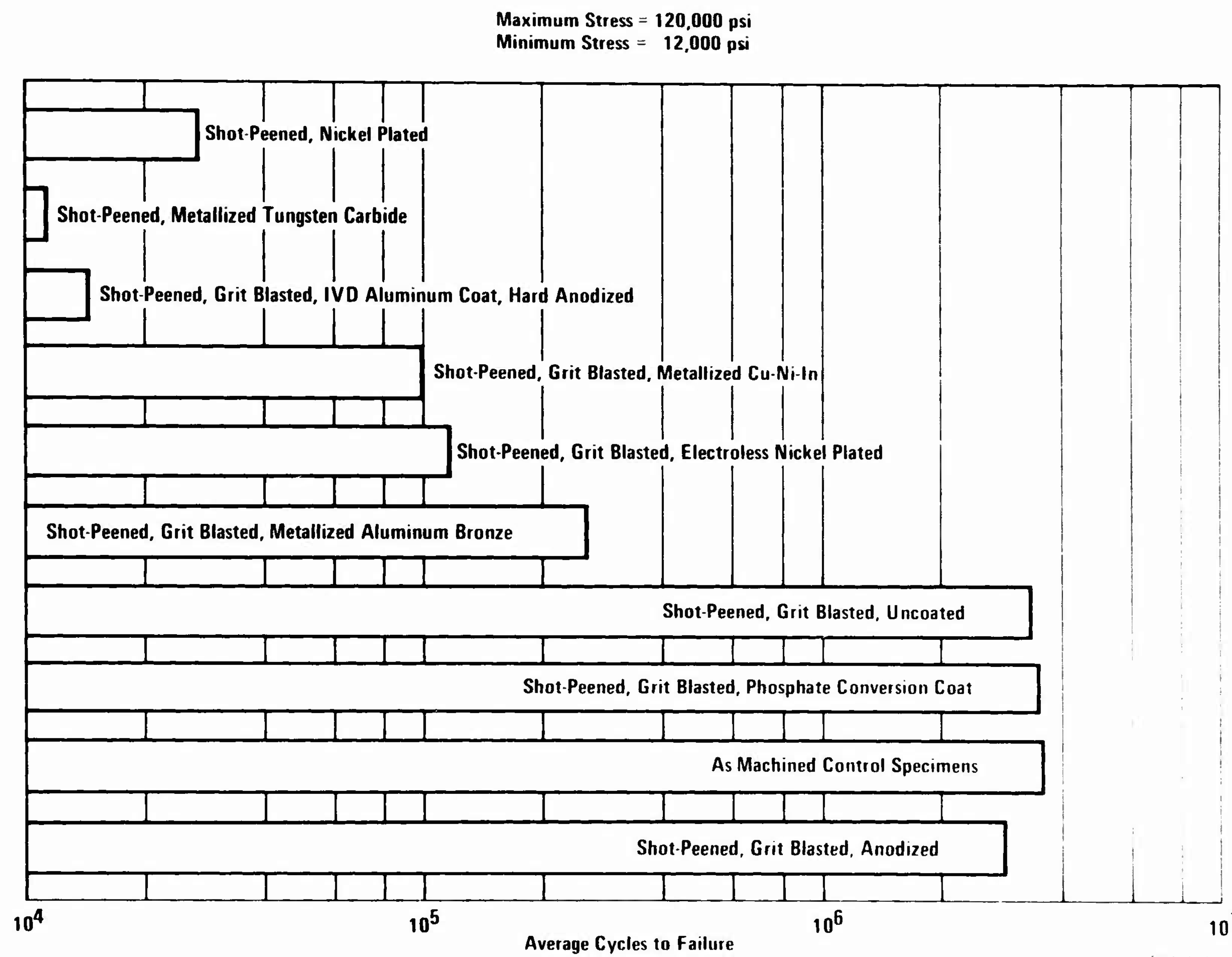


Figure 18 Task II Fatigue Testing

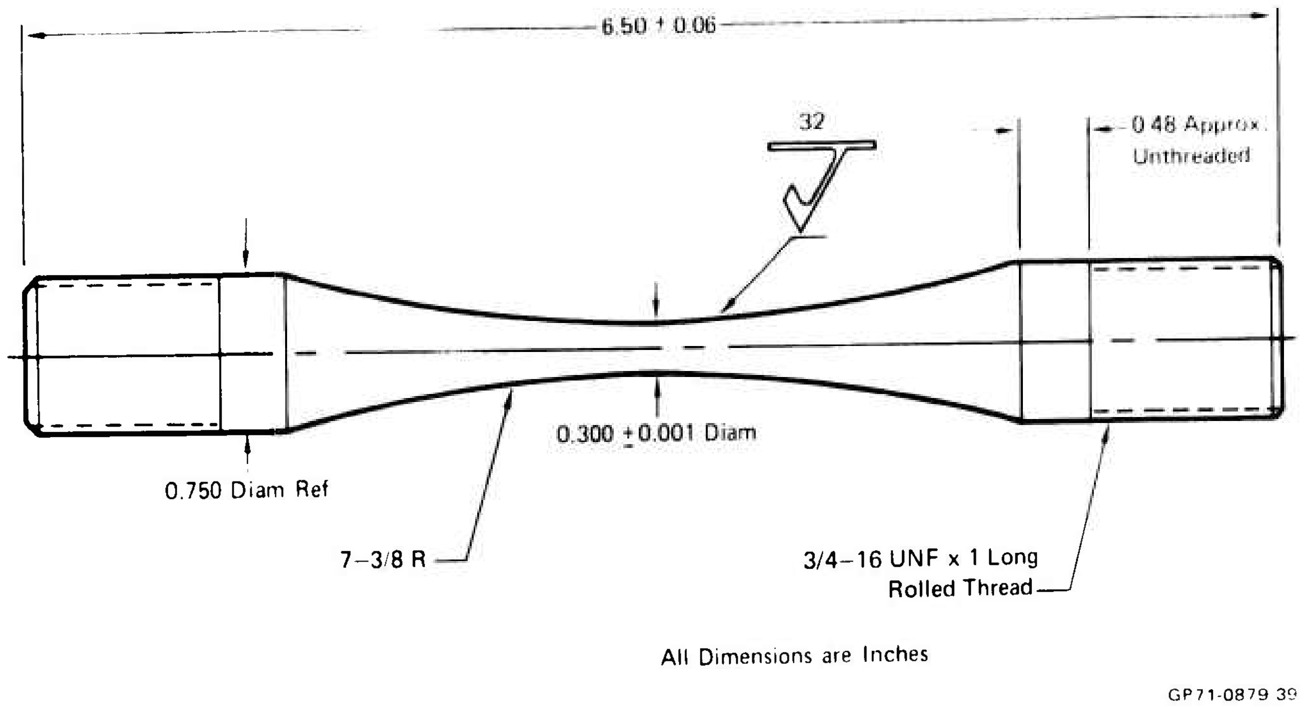


Figure 19 Fatigue Specimen – Task II

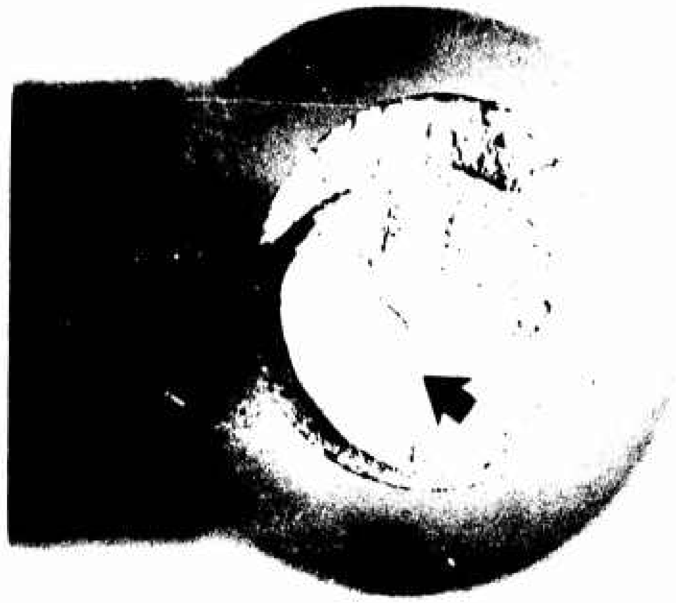
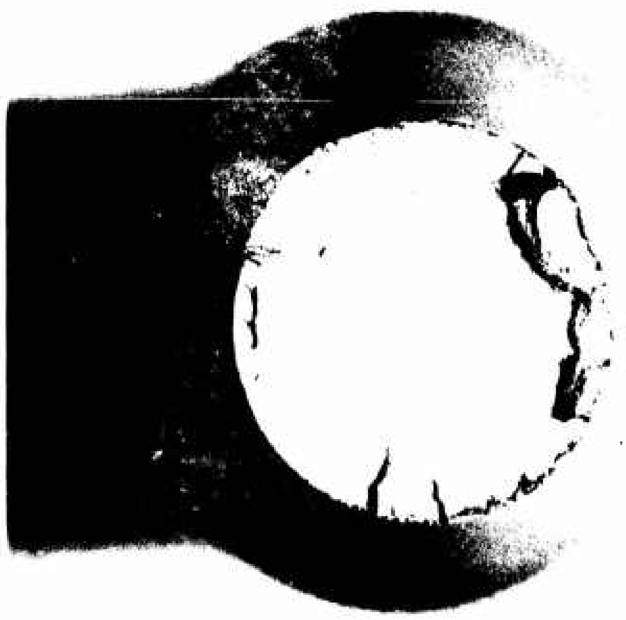


Figure 20 Fracture Surface of Unnotched Fatigue Specimen, Fluoride Phosphate Conversion Coated



GP71-0879-40

Figure 21 Fracture Surface of Unnotched Fatigue Specimen, IVD Aluminum Plated and Hardcoat Anodized

5.0 FRETTING EVALUATION, TASK III

This task had the objective of evaluating the three coatings selected in Task II using the fretting specimen and parameters developed in Task I. The ability of the coatings to prolong fatigue life by eliminating fretting damage was judged in comparison with Task I data.

The test plan called for specimens of Ti-6Al-6V-2Sn to be coated with each of three coatings and fatigue tested. From this testing, one coating was selected. The performance of this coating was then further verified on the alloys Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo.

5.1 Specimen Preparation - During Task I, seven specimens broke prematurely due to fretting damage between the loading pin and the inside diameter of the loading hole in the specimen lug end. For this task, a steel bushing was added to the specimen design, as shown in Figure 22. Tolerances were controlled for interference between bushing and specimen of 0.0010-0.0025 inches. To eliminate scarring the inside of the loading hole, the bushings were shrunk into place. Specimen fabrication was essentially the same as Task I except that Taper-Lok fastener holes were machine reamed and countersunk using a Spacematic drill Model J-200. This gave a 32 rms finish and replaced the drill press - hand ream operation used in Task I.

After machining and reaming of fastener holes, the following procedure was used to prepare the specimen for testing:

- Mask the ends of each specimen so that only a 3-1/2 inch center gauge section is exposed.
- Plug fastener holes.
- Shot peen and grit blast, remove maskant.
- Mask inside diameter of fastener holes.
- Apply anodic or conversion coating, if required.
- Mask ends as abov .
- Apply Molykote 106 lubricant to center section.
- Remove all maskant.
- Shrink fit steel bushings in lug holes.
- Assemble specimen and doublers.

Doublers were processed the same way except that both sides were anodic or conversion coated but only the bearing sides were solid film lubricated.

A Tiodize-Molykote 106 coated specimen is shown in Figure 23 as it appeared after fatigue testing. The change in shading at the center marks the area masked for shot-peening and grit-blasting.

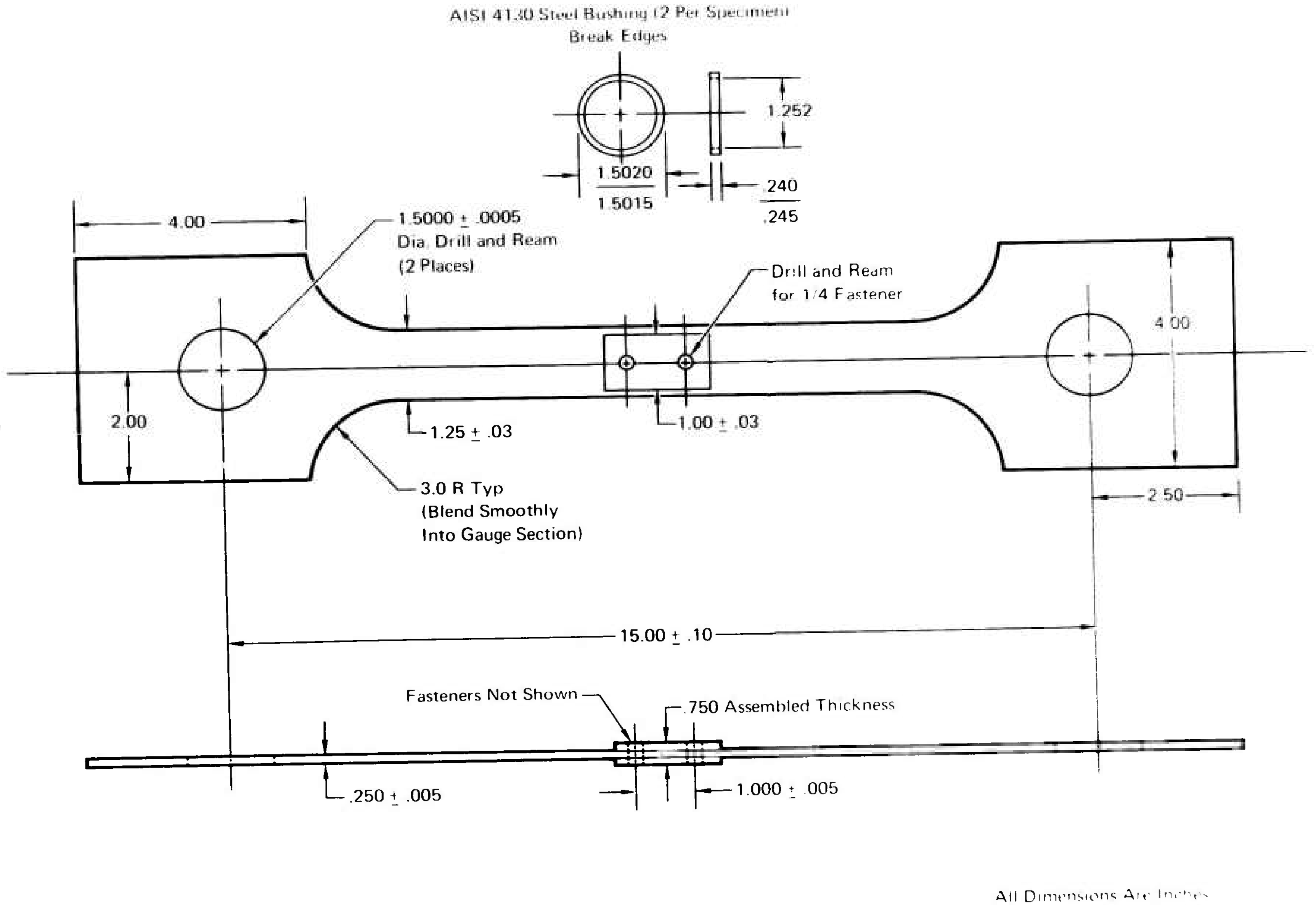


Figure 22 Redesigned Fatigue Specimen - Task III

GP71-0879-42

Figure 23 Task III Specimen: Tiodized-Molykote 106 Coated, after Fatigue Test

The Ti-6Al-6V-2Sn alloy used was from the same heat tested in Task I. Ti-6Al-2Sn-4Zr-6Mo plate material (duplex annealed) was obtained from Titanium Metals Corporation Heat K-0800. Chemical analysis was:

C - .021%	H - .007%
Fe - .07%	Zr - 4.0%
N - .009%	Sn - 1.9%
Al - 5.9%	O - .10%
Mo - 6.0%	

Longitudinal mechanical properties (all specimens were machined with the long dimension parallel to the longitudinal grain) tested:

Fty - 164 KSI

Ftu - 173 KSI

Elongation - 18.0%

Ti-6Al-4V plate material (annealed) was from Reactive Metals Inc. Heat No. 302295.

C - .03%	V - 4.4%
Fe - .08%	H - .011%
N - .013%	O - .121%
Al - 6.3%	

Mechanical properties tested:

Fty - 141 KSI

Ftu - 151 KSI

Elongation - 10.0%

5.2 Ti-6Al-6V-2Sn Test Results - The improvement in fatigue life attributed to the prevention of fretting damage was so dramatic that it became necessary to limit the test duration. As noted in Table 6, testing was stopped at about 2-1/2 million cycles in most cases. One specimen (No. 17) failed at 780,000 cycles and is considered within normal fatigue scatter. Two specimens (Nos. 5 & 12) were tested at 70.4 KSI stress (high stress of Task I) and failed. However, all of these specimens had fracture origins at the fastener hole. Fretting did not occur between the faying surfaces. The specimens are shown in Figures 24, 25, and 26.

As seen in Table VI, the coatings applied were effective in preventing fretting failures which occurred in Task I uncoated specimens at about 270,000 cycles. After testing, the disassembled surfaces showed no sign of wearing through the solid film lubricant. Typical examples are shown in Figures 27 and 28. The Molykote

TABLE VI - TASK III FATIGUE TEST RESULTS

Ti-6Al-6V-2Sn Alloy

Specimen No.	Coating	Cycles
1	Molykote 106 over Tiodize	2,756,000
2	Molykote 106 over Tiodize	4,620,000
3	Molykote 106 over Tiodize	2,511,000
4	Molykote 106 over Tiodize	2,526,000
5	Molykote 106 over Tiodize	* 106,000
6	Molykote 106 over Tiodize	2,539,000
7	Molykote 106	2,690,000
8	Molykote 106	7,002,000
9	Molykote 106	2,508,000
10	Molykote 106	2,514,000
11	Molykote 106	2,525,000
12	Molykote 106	* 47,000
13	Molykote 106 over Fluoride-Phosphate	2,531,000
14	Molykote 106 over Fluoride-Phosphate	2,501,000
15	Molykote 106 over Fluoride-Phosphate	2,530,000
16	Molykote 106 over Fluoride-Phosphate	2,529,000
17	Molykote 106 over Fluoride-Phosphate	* 780,000
18	Molykote 106 over Fluoride-Phosphate	2,532,000

* Specimen failed at number of cycles noted.
All other specimens did not fail.

Fatigue Test Conditions: 30 cycles per second frequency; 1 inch between fasteners; Ti-6Al-4V Taper-Lok Fasteners; 38.4 ksi Tensile Gross Stress (max.); 3.8 ksi Compressive Gross Stress (min.).

Note: Specimens No. 5 and 12 were tested at 70.4 ksi Tensile Gross Stress (max.) and 7.0 ksi Compressive Gross Stress (min.).

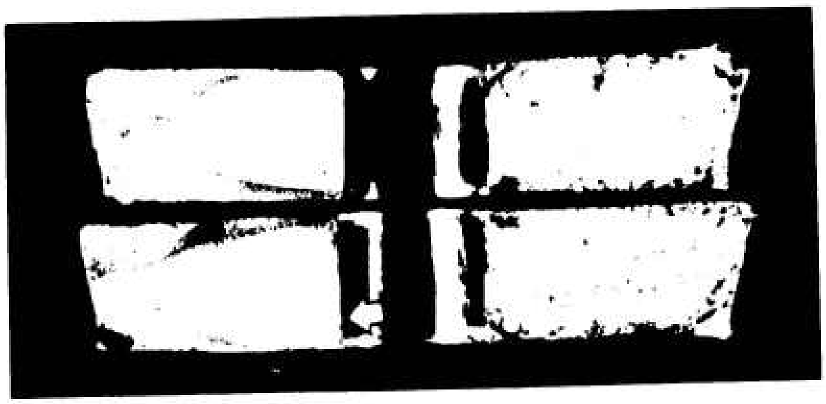


Figure 24 Specimen 5 - Task III

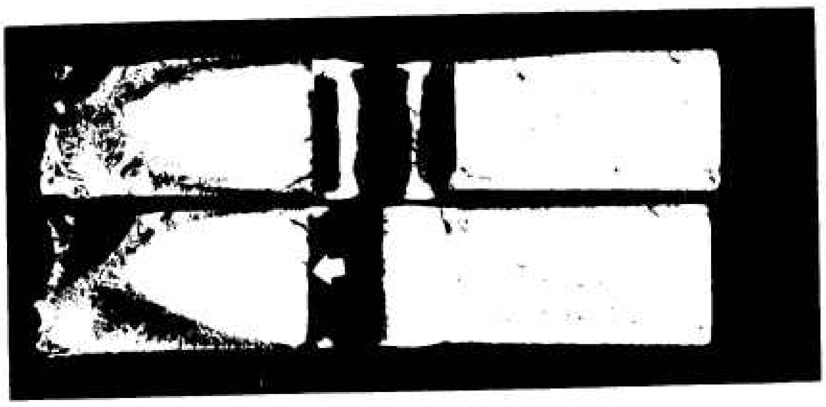
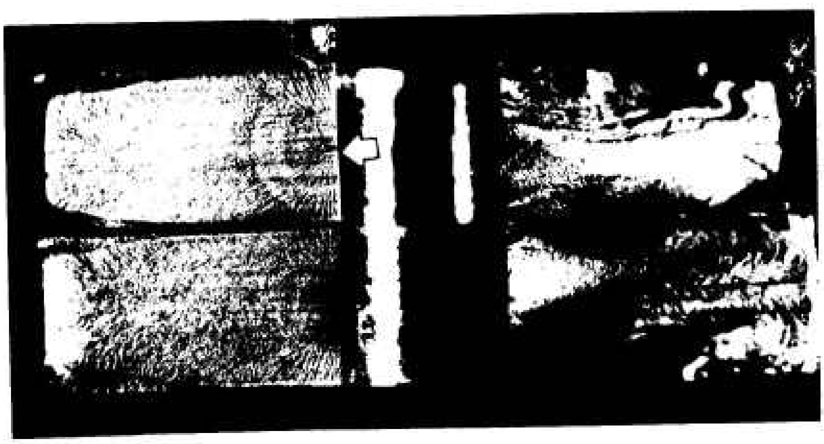
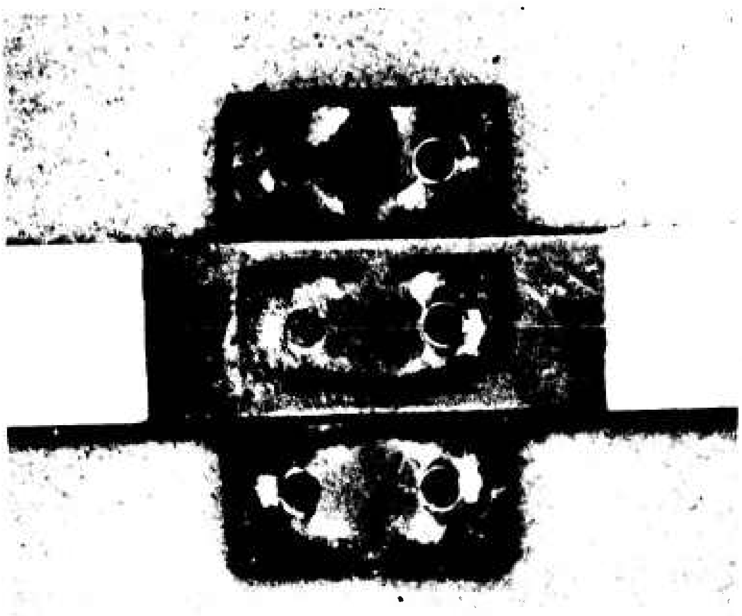


Figure 25 Specimen 12 - Task III



GP71-0879-23

Figure 26 Specimen 17 - Task III

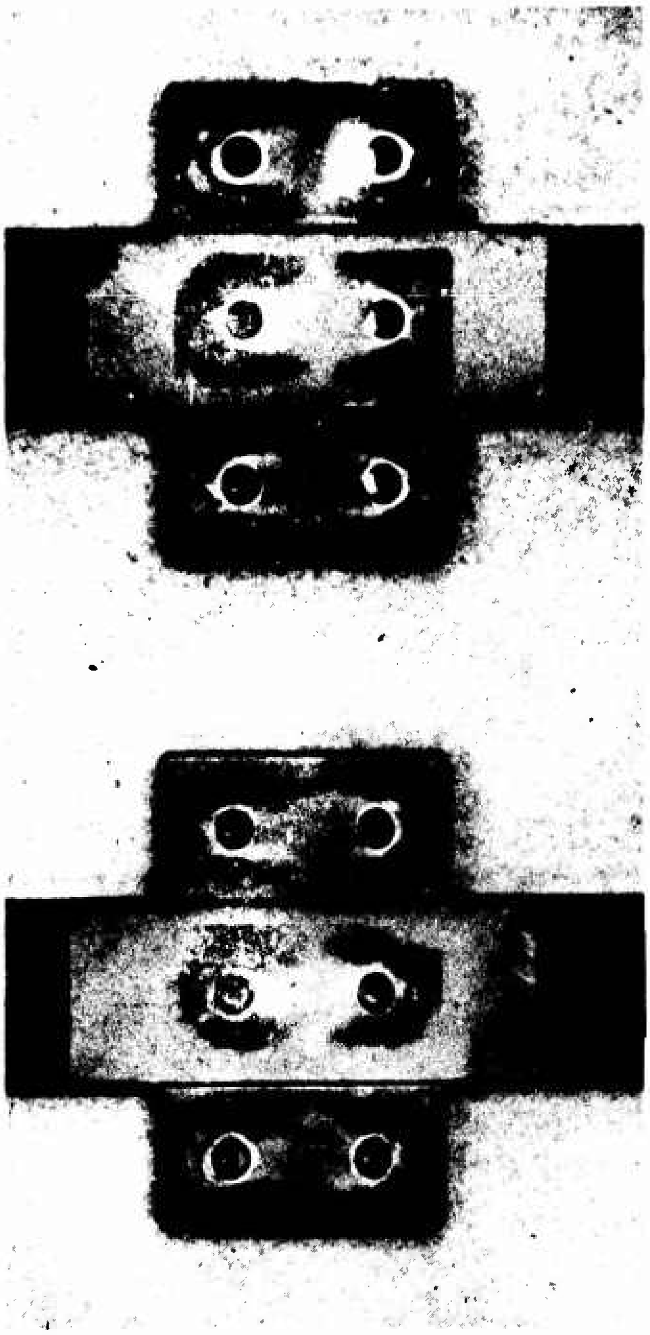


After
7,002,000
Cycles

After
2,508,000
Cycles

GP71-0879-21

Figure 27 Gauge Section of Molykote 106 Coated Specimens, Disassembled after Testing



After
2,539,000
Cycles

After
4,620,000
Cycles

GP71-0879-22

Figure 28 Gauge Section of Tiodize - Molykote 106 Coated Specimens, Disassembled after Testing

106 lubricant appears to be thinning in some areas although it is not clear whether this condition resulted from the test or was caused during disassembly by transfer of lubricant from one surface to the other.

Since there was no apparent advantage, under these test conditions, in anodizing or conversion coating, Molykote 106 without undercoat was chosen for performance verification testing on the other two alloys.

5.3 Ti-6Al-2Sn-4Zr-6Mo Test Results - Five specimens were prepared from Ti-6Al-2Sn-4Zr-6Mo alloy. Coating with Molykote 106 dry film lubricant was preceded by shotpeening and grit-blasting. Fretting fatigue tests at 38.4 KSI gross stress produced no failures. The results are shown in Table VII. As in the previous set of specimens, there was no fretting damage at the faying surfaces and the dry film lubricant was not worn through when the parts were disassembled.

5.4 Ti-6Al-4V Test Results - Seven specimens were fabricated from Ti-6Al-4V alloy. During testing, a wide scatter band of cycles to failure resulted. As shown in Table VIII, this data ranged from 81,000 cycles to no failure at 10 million cycles. Because it was suspected that the early failures may have been related to tiny tool marks on the inside of the fastener hole, the fastener holes were polished on specimen 30. This resulted in a fastener interference fit of 0.0025 inch. In fatigue testing this specimen did not fail at 10 million cycles.

Of the four failed specimens, none had fracture origins at the faying surfaces. There was no fretting damage on any of the specimens. On each of these four, fracture originated at the inside of the fastener hole. These origins are shown in figures 29, 30 and 31 (Specimen 27 was destroyed for analysis). There are three factors that are judged to have contributed to these failures:

a) The hydrogen content of the failed specimens was found to be 218 ppm.

b) The grain size of the material, although not unusual for annealed plate, is noticeably coarser than the other two alloys tested.

c) Under the microscope there appears to be a correlation of fracture origins with tool marks incurred during fastener hole preparation.

Although the above factors may not have separately caused the failures, it is concluded that they interacted to initiate early fracture on these specimens and cause the wide scatter in results.

In summary, Task III clearly shows that a simple application of dry film lubricant, with or without a bonding undercoat, will effectively prevent fretting - fatigue failures under the test conditions established in Task I

TABLE VII - TASK III FATIGUE TEST RESULTS

Ti-6Al-2Sn-4Zr-6Mo Alloy

Specimen No.	Coating	Cycles
19	Molykote 106	2,539,000
20	Molykote 106	2,500,000
21	Molykote 106	2,500,000
22	Molykote 106	7,084,000
23	Molykote 106	10,452,000

(No failures occurred at the number of test cycles shown.)

Fatigue Test Conditions: 30 cycles per second frequency; 1 inch between fasteners; Ti-6Al-4V Taper Lok Fasteners; 38.4 ksi Tensile Gross Stress (max.); 3.8 ksi Compressive Gross Stress (min.).

TABLE VIII - TASK III FATIGUE TEST RESULTS

Ti-6Al-4V Alloy

Specimen No.	Coating	Cycles to Failure
24	Molykote 106	81,000
25	Molykote 106	5,039,000
26	Molykote 106	* 2,810,000
27	Molykote 106	739,000
28	Molykote 106	260,000
29	Molykote 106	* 2,688,000
30	Molykote 106	**10,000,000

Fatigue Test Conditions: Thirty cycles per second frequency; 1 inch between fasteners; Ti-6Al-4V Taper-Lok fasteners; 38.4 ksi Tensile gross stress (max.); 3.8 ksi Compressive gross stress (min.).

* Specimens 26 and 29 did not fail.

** The fastener holes on Specimen 30 were polished prior to assembly. No failure occurred at 10 million cycles.

Figure 29   Specimen 24 - Task III

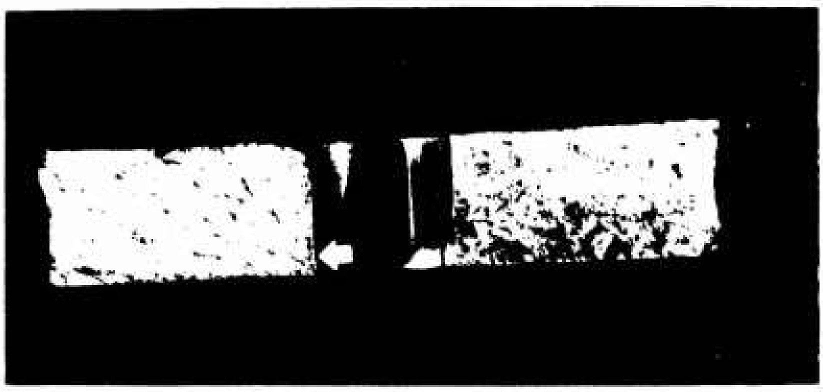
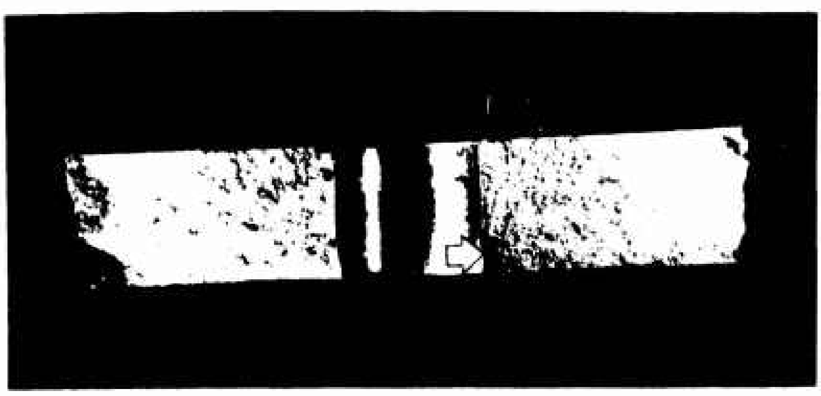


Figure 30   Specimen 25 - Task III



GP71-0879-19

Figure 31   Specimen 28 - Task III

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions.

a) Due to differences in size and types of fasteners, material, etc. there are design variations in airframe joints that have a significant effect on the severity of fretting. The importance of fretting in specific structures may range from insignificant to critical.

b) The fretting fatigue specimen used in Tasks I and III accurately simulates the design parameters which control the fretting mechanism in a structural joint.

c) Based on fractographic analysis of the specimens and scanning electron microscope examination of the surfaces there is no difference in the fretted surfaces produced by different test parameters.

d) A threshold number of fatigue exposure cycles is required before fretting damage becomes critical. When structural parameters, such as the combination of Taper-Lok fasteners and low stress in Task I, extend the fatigue life of a joint to this limit, fretting damage can be the cause of fatigue failure.

e) Within the test limits, fastener material and torque, load transfer, and testing frequency did not have a significant effect on fretting induced fatigue failure.

f) In the fretting critical situation, the fatigue life of the joint is severely shortened. This was graphically demonstrated by the Task I control specimens and coated specimens of Task III which ran 10 times as long as unprotected test specimens.

g) Coatings are available that have good adhesion on titanium alloys, are applicable to complex shapes, and have no significant hydrogen pickup during processing.

h) The coatings tested have no appreciable effect on the tensile properties of Ti-6Al-6V-2Sn; however, all seriously degraded the fatigue resistance of the titanium alloy except for the conversion coating and anodized coating.

i) Effective anti-fretting coatings are available. As demonstrated in Task III, these coatings eliminated fretting surface damage as a cause of fatigue fracture.

j) Molykote 106 dry film lubricant applied over a shot-peened, grit-blasted surface was verified as effective in preventing fretting failure on Ti-6Al-4V and Ti-6Al-2Sn-4Zn-6Mo alloys.

6.2 Recommendations.

a) Further testing of uncoated specimens should be conducted to evaluate the effect of high load transfer at high stress, varying surface finishes and environmental conditions.

b) Additional tests on Ti-6Al-4V alloy are required to verify or eliminate the data scatter obtained in Task III.

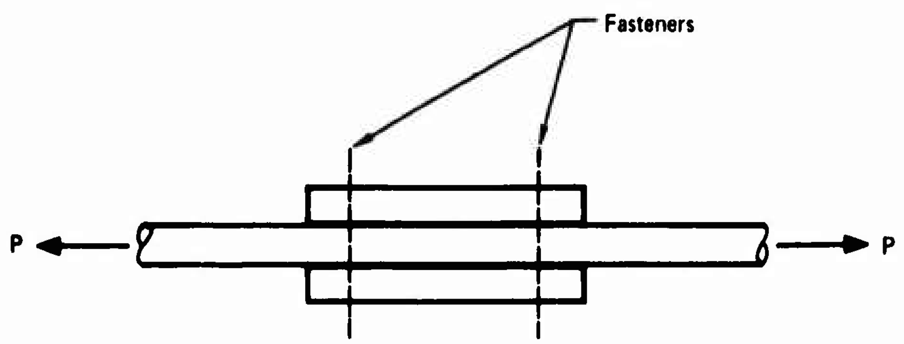
c) Additional testing of the effect of coatings on fatigue properties should include notched fatigue specimens and lower stress levels since in some cases these conditions would more closely parallel design situations.

d) Fretting effects must be considered in airframe design. Considerations of stress concentration, load, etc. may override the importance of fretting in specific applications so that the final criterion should be tests of the actual structure to required spectrum fatigue loads.

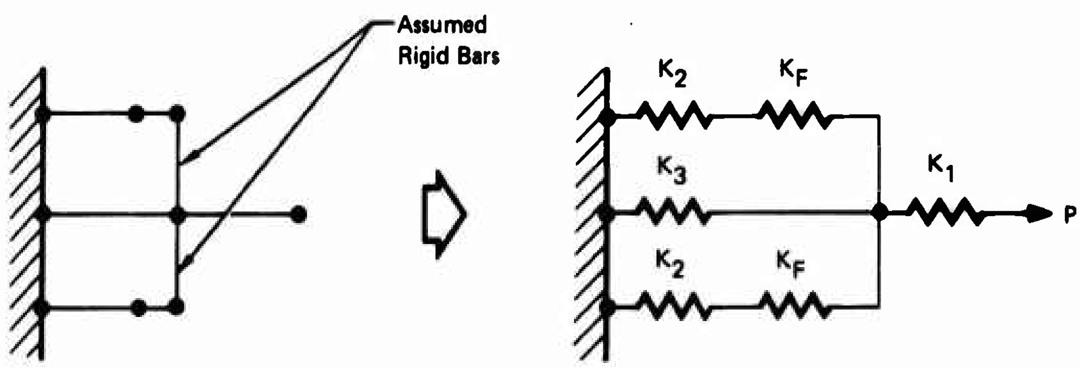
7.0 APPENDIX

Appendix A - Elastic Analysis of Task I Fatigue Specimen

An elastic analysis of the joint specimen to determine the load transfer as a function of fastener spacing was performed using empirically developed data.



The following model of the above jointed specimen was made:



To estimate the spring constant of the fastener, an analytical expression presented by Voyt (References 1, 2, 3) for estimating the linear load deflection characteristics of double shear bolted or riveted joints in light alloy structures was used:

$$K_F = \frac{P_b}{\delta_{eb}} = \frac{Ed}{f}$$

GP71-0879-18

K_F = Spring Constant of Fastener

f = Semi-Empirical Factor = $2.5 + \left[2 - 0.8 \frac{t_1}{t_2} \right] \frac{d}{t_2}$

E = Modulus of Elasticity of Plate Material

d = Hole Diameter

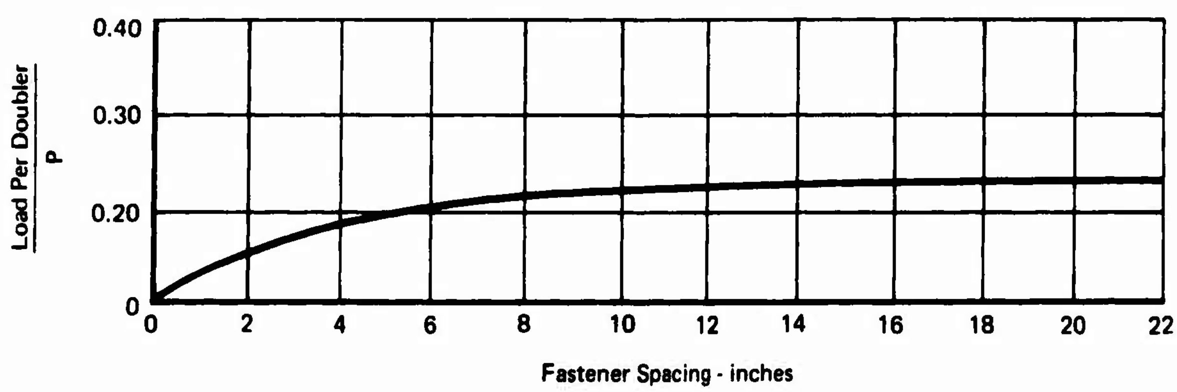
t_1 = Outer Plate Thickness

t_2 = Inner Plate Thickness

P_b = Load at Joint

δ_{eb} = Elastic Deflection of Bolt

The substantiation of the semi-empirical factor f is handicapped by lack of sufficient experimental data. An analytical approach for estimating the nonlinear effects apparently does not exist. The following graph presents results of elastic analysis.



References

(1) "Analytical Design Methods for Aircraft Structural Joints," AFFDL-TR-67-184, January 1968.

(2) "Fatigue Prediction Study," WADD TR-61-153, January 1962

(3) Voyt, F. "The Load Distribution in Bolted or Riveted Joints in Light Alloy Structures," NACA-TR-1135, April 1947.

GP71-0879-46

Appendix B

Table B-1 Task I Fatigue Test Data

Fastener Data: Type (3)	Fastener Data: Fit	Fastener Data: Torque (in.-lb)	Specimen No.	Gross Stress (ksi)	Tensile (2) Load Transfer (% Per Doubler)	Cycles To Failure	Fracture Description
Preliminary Tests (30 cps, 2 Inch Doubler)							
Ti-Screw	0.0005/0.0015 Clearance	70	A	96.0		2,850	Origin at Fastener Hole
Ti-Screw		70	B	80.0		4,620	Origin at Fastener Hole
Ti-Screw		70	C	70.4		12,520	Origin at Fastener Hole
Ti-Screw		70	D	35.2		49,000	Origin at Fastener Hole
Ti-Screw		70	E	28.8		424,000	Origin at Surface Fretting Damage
Ti-Screw		70	F	35.2		240,000	Origin at Surface Fretting Damage
a) Comparison of Fastener Type (30 cps, 2 Inch Doubler)							
Ti-HiLok	0.0005/0.0015 Clearance	60	1	70.4	(1.2%)	12,000	Origin at Fastener Hole
Ti-HiLok		60	2	70.4		13,000	Origin at Fastener Hole
Ti-HiLok		60	3	70.4		11,370	Origin at Fastener Hole
Ti-Screw	0.0005/0.0015 Clearance	70	5	70.4	2%	10,000	Origins at Fastener Hole and on Surface
Ti-Screw		70	22	70.4		9,000	Origin at Fastener Hole
Ti-Screw		70	23	70.4		11,000	Origin at Fastener Hole
Ti-Screw		70	C	70.4		12,520	Origin at Fastener Hole
Ti-TaperLok	0.0039/0.0046 Interference	120	7	70.4		83,000	Origin at Surface Fretting Damage
Ti-TaperLok		120	8	70.4	6.8%	39,000	Broke Out of Gauge Section
Ti-TaperLok		120	9	70.4	5.6%	57,000	Broke Out of Gauge Section
Ti-TaperLok		120	8-2	70.4	5.5%	60,000	Origin at Surface Fretting Damage
Ti-TaperLok		120	9-2	70.4	4.5%	41,000	Broke Out of Gauge Section
b) Comparison of Fastener Material (30 cps, 2 Inch Doubler)							
Steel-TaperLok	0.0039/0.0046 Interference	120	10	70.4		106,000	Origin at Fastener Hole
Steel-TaperLok		120	11	70.4	9.2%	32,000	Broke Out of Gauge Section
Steel-TaperLok		120	12	70.4		76,000	Origin at Surface Fretting Damage
Steel-TaperLok		120	11-2	70.4	(8.8%)	85,000	Origin at Surface Fretting Damage
c) Comparison of Fastener Interference Fit (30 cps, 2 Inch Doubler)							
Ti-HiLok	0.001/0.002 Interference	60	13	70.4		8,000	Origin at Fastener Hole
Ti-HiLok		60	14	70.4		11,400	Origin at Fastener Hole
Ti-HiLok		60	15	70.4		17,700	Origin at Fastener Hole

GP71 0879-1

Table B-1 Task I Fatigue Test Data (Continued)

Fastener Data: Type [3]	Fit		Torque (in.-lb)	Specimen No.	Gross Stress (ksi)	Tensile[2] Load Transfer (% Per Doubler)	Cycles To Failure	Fracture Description
d) Comparison of Fastener Installation Torque (30 cps, 2 Inch Doubler)								
Ti-Screw	0.0005/0.0015	Clearance	10[1]	16	70.4	(1.7%)	7,000	Origin at Fastener Hole
Ti-Screw			10[1]	17	70.4		4,680	Origin at Fastener Hole
Ti-Screw			10[1]	18	70.4		7,200	Origin at Fastener Hole
e) Comparison of Stress Level (30 cps, 2 Inch Doubler)								
Ti-HiLok	0.0005/0.0015	Clearance	60	19	38.4	3.3%	263,000	Origin at Surface Fretting Damage
Ti-HiLok			60	20	38.4		223,000	Origin at Surface Fretting Damage
Ti-HiLok			60	21	38.4		227,000	Origin at Surface Fretting Damage
Ti-Screw	0.0005/0.0015	Clearance	70	24	38.4		87,000	Origin on Surface at Fretting Damage near Fastener Hole Also in I.D.
Ti-Screw			70	4	38.4	1.1%	259,000	Origin at Fastener Hole
Ti-Screw			70	4-2	38.4	1.7%	113,000	Origin at Fastener Hole
Ti-Screw			70	6	38.4		62,000	Origin at Fastener Hole
Ti-TaperLok	0.0039/0.0046	Interference	120	25	38.4	9.3%	193,000	Origin at Surface Fretting Damage
Ti-TaperLok			120	26	38.4	8.6%	208,000	Origin at Surface Fretting Damage
Ti-TaperLok			120	27	38.4		487,000	Origin at Surface Fretting Damage
Steel-TaperLok	0.0039/0.0046	Interference	120	28	38.4	12.5%	387,000	Origin at Surface Fretting Damage
Steel-TaperLok			120	29	38.4		213,000	Origin at Surface Fretting Damage
Steel-TaperLok			120	30	38.4		305,000	Broke Out of Gauge Section
Steel-TaperLok			120	30-2	38.4		310,000	Origin at Surface Fretting Damage
Ti-HiLok	0.001/0.002	Interference	60	31	38.4	5.5%	168,000	Origin at Fastener Hole
Ti-HiLok			60	32	38.4		89,000	Origin at Fastener Hole
Ti-HiLok			60	33	38.4		112,000	Origin at Fastener Hole
Ti-Screw	0.0005/0.0015	Clearance	10[1]	34	38.4		67,000	Origin at Fastener Hole
Ti-Screw			10[1]	35	38.4		61,000	Origin at Fastener Hole
Ti-Screw			10[1]	36	38.4		61,000	Origin at Fastener Hole

GP71-0879-2

Table B-1 Task I Fatigue Test Data (Continued)

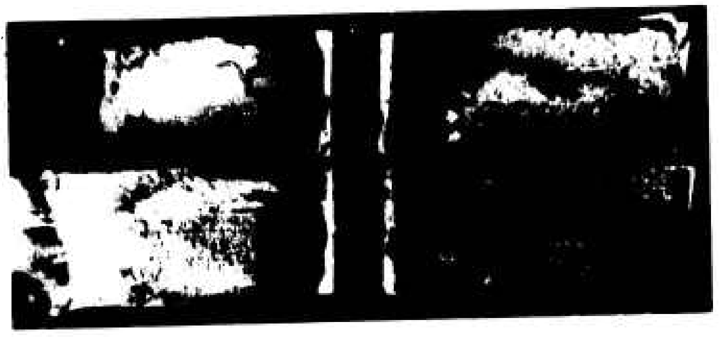
Fastener Data			Specimen No.	Gross Stress (ksi)	Tensile(2) Load Transfer (% Per Doubler)	Cycles To Failure	Fracture Description
Type (3)	Fit	Torque (in.-lb)					
f) Comparison of Cyclic Loading Frequency (5cps, 2 Inch Doubler)							
Ti-TaperLok	0.0039 / 0.0046 Interference	120	37	38.4		645,900	Origin at Surface Fretting Damage
Ti-TaperLok		120	39	38.4		249,500	Origin at Surface Fretting Damage
Ti-TaperLok		120	40	38.4		245,790	Origin at Surface Fretting Damage
Ti-TaperLok		120	38	70.4	(5.1%)	55,460	Origin at Surface Fretting Damage
Ti-TaperLok		120	41	70.4		76,290	Origin at Surface Fretting Damage
Ti-TaperLok		120	42	70.4		Loading Error, Broke on Startup	
g) Comparison of High Load Transfer (30 cps, 7 Inch Doubler)							
Ti-TaperLok	0.0039 / 0.0046 Interference	120	43	38.4	(22.9%)	228,000	Origin at Surface Fretting Damage
Ti-TaperLok		120	44	38.4	(23.0%)	258,000	Origin at Surface Fretting Damage
Ti-TaperLok		120	45	38.4		231,000	Broke Out of Gauge Section
Ti-TaperLok		120	46	70.4		36,000	Origin at Surface Fretting Damage Fastener Also Fractured
Steel-TaperLok	0.0039 / 0.0046 Interference	120	47	38.4	(23.0%)	482,000	Origin at Surface Fretting Damage
Steel-TaperLok		120	48	38.4	(23.4%)	227,000	Origin at Surface Fretting Damage
Steel-TaperLok		120	43A	38.4		238,000	Origin at Surface Fretting Damage
h) Control Specimens (30 cps, 2 Inch Doubler, Nylatron Liners)							
Ti-TaperLok	0.0039 / 0.0046 Interference	120	50	38.4		2,500,000+	Did Not Fail, Test Stopped
Ti-TaperLok		120	49	38.4		634,000	Origin at Burr in Fastener Hole
Ti-TaperLok		120	51	38.4		290,000	Broke Out of Gauge Section
Ti-TaperLok		120	51-2	38.4		5,314,000	Broke Out of Gauge Section

Notes: (1) 10 In.-Lb in excess of free running torque (20 In.-Lb average)
(2) Readings in parentheses were obtained during fatigue tests, all others were made in a tensile machine prior to testing. All were based only on axial tensile loads
(3) Ti-HiLok (HL-11VV-97-8-12), Ti-Screw (NAS-664-13HT), Ti-TaperLok (TLV-100-4-12-D2), Steel-TaperLok (TLC 100-4-12-D2)

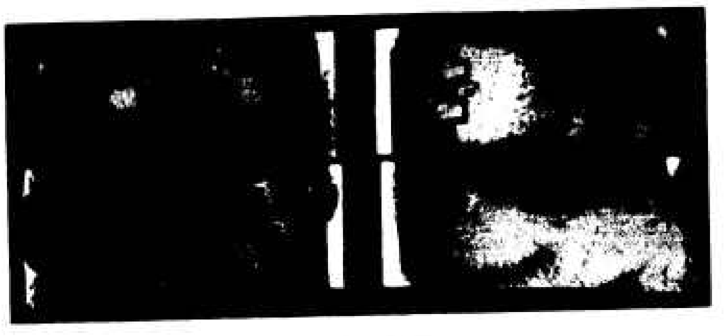
GP71-0879-3

Appendix C

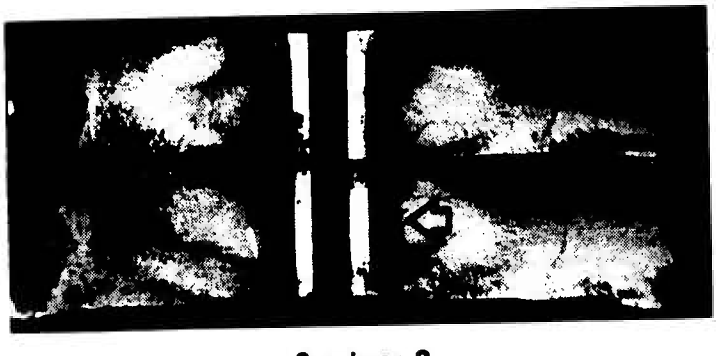
Task I Fatigue Test - Fracture Surface of Test Specimens



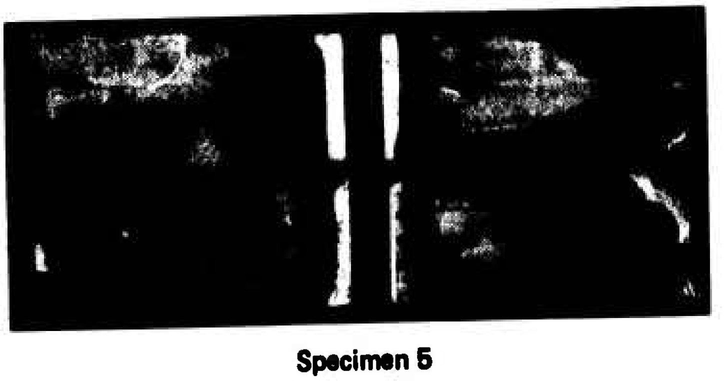
Specimen 1



Specimen 2

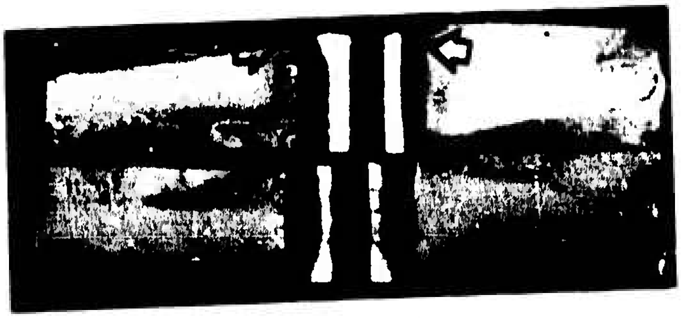


Specimen 3

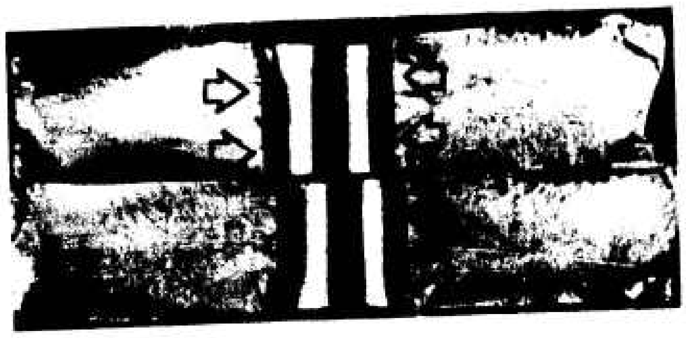


Specimen 5

GP71-0879-4

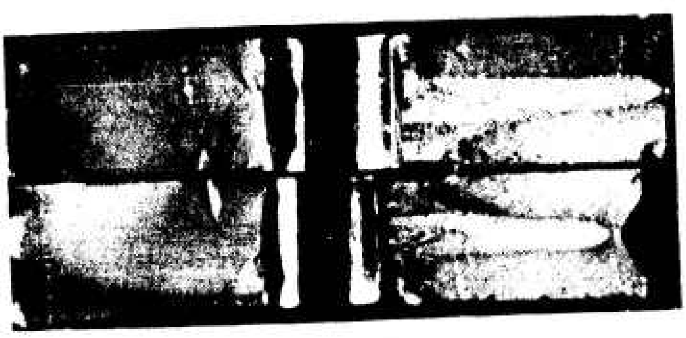


Specimen 22



Specimen 23

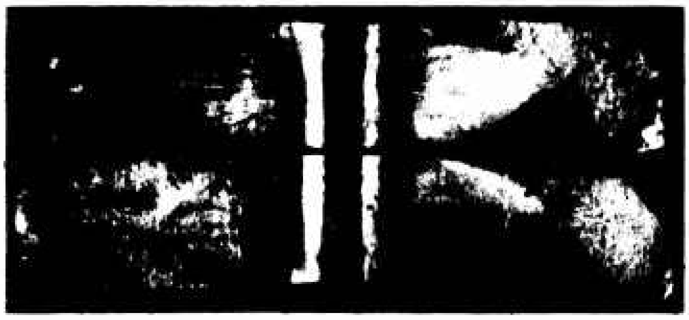
Specimen C



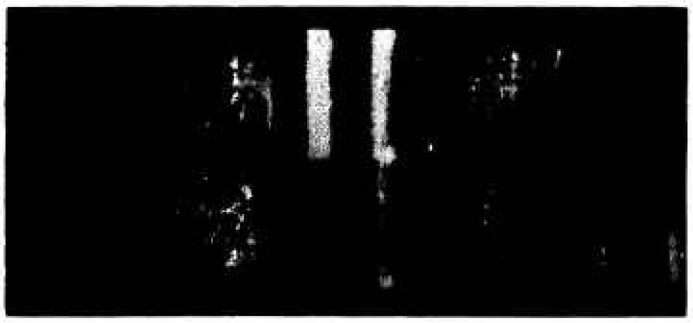
Specimen 7

GP71-0879-5

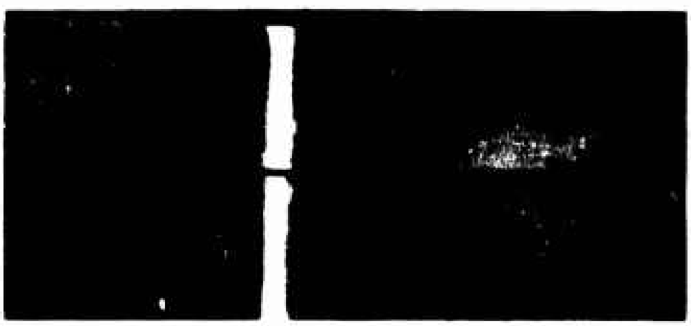
Specimen 8-2



Specimen 10

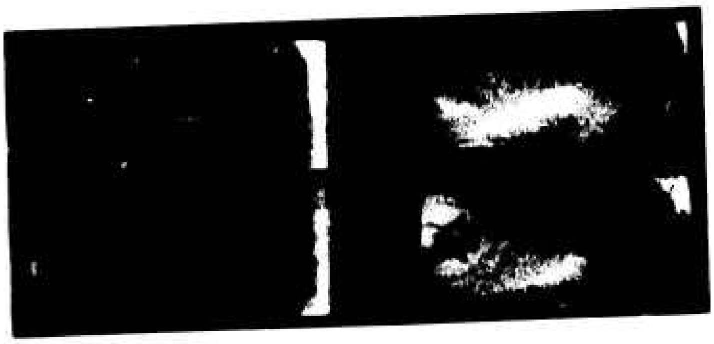


Specimen 12

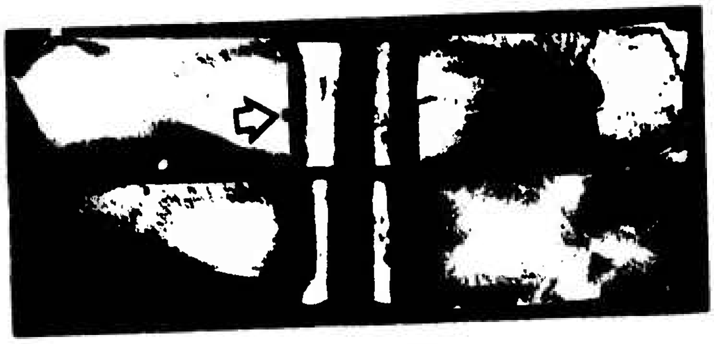


Specimen 11-2

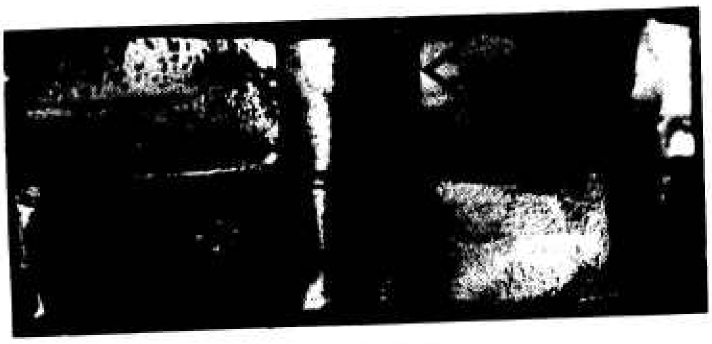
GP71-0879-6



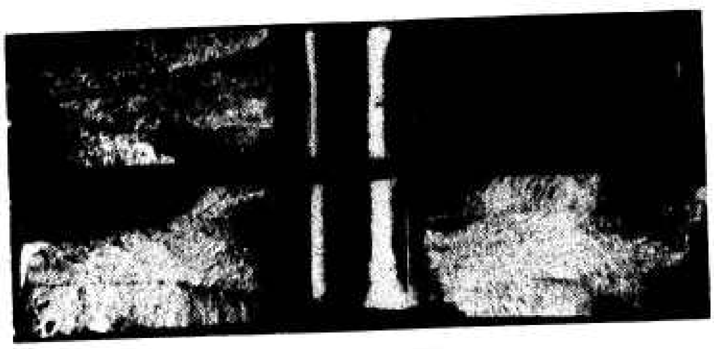
Specimen 13



Specimen 14

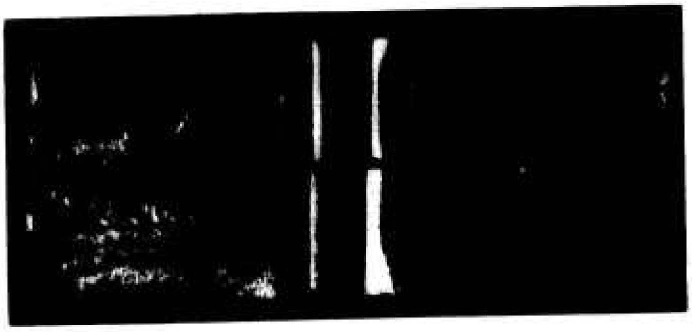


Specimen 15

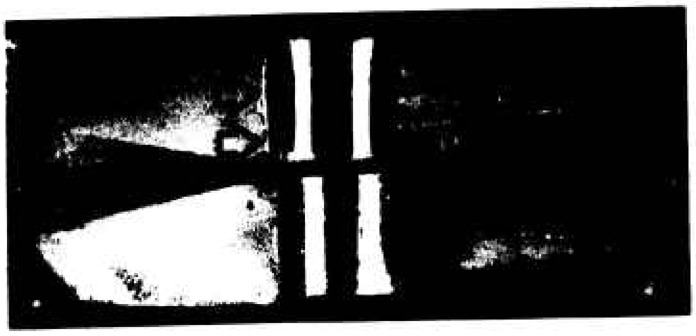


Specimen 16

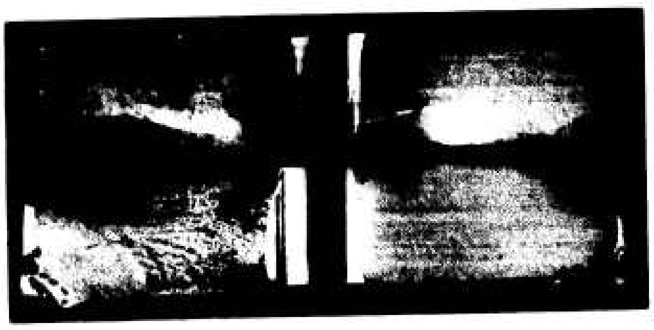
GP71-0879-7



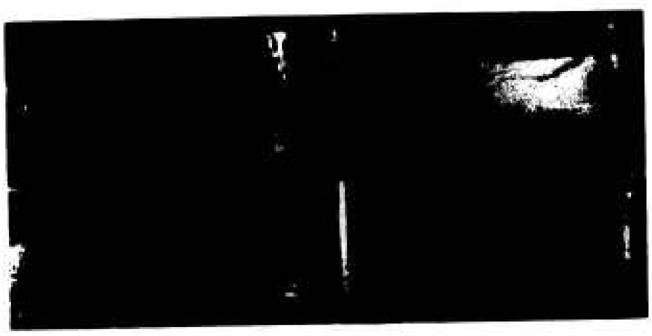
Specimen 17



Specimen 18

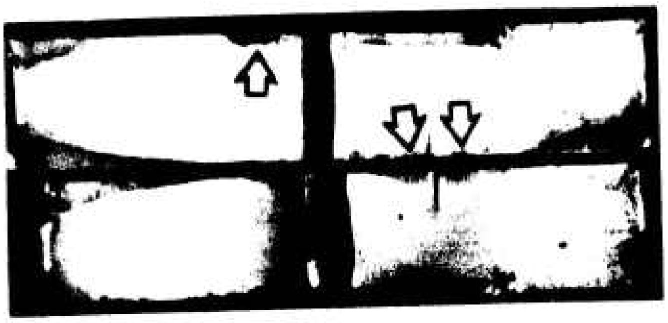


Specimen 19

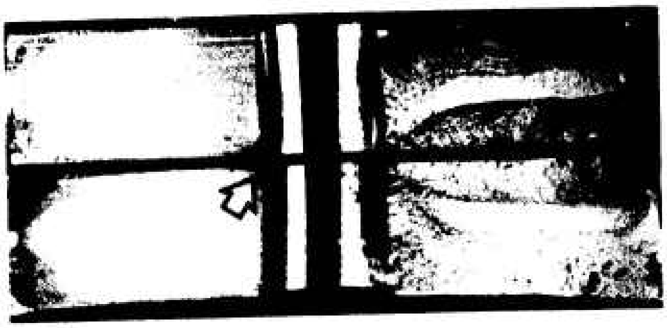


Specimen 20

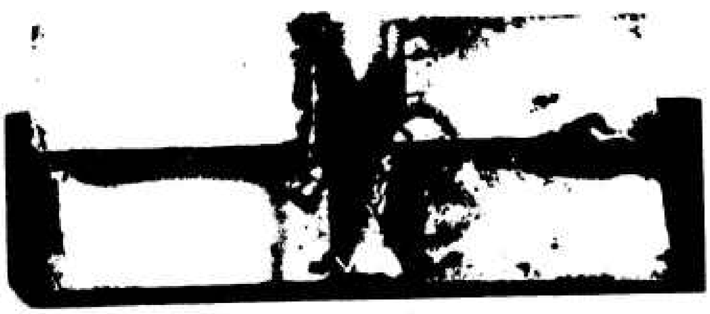
GP71-0879-8



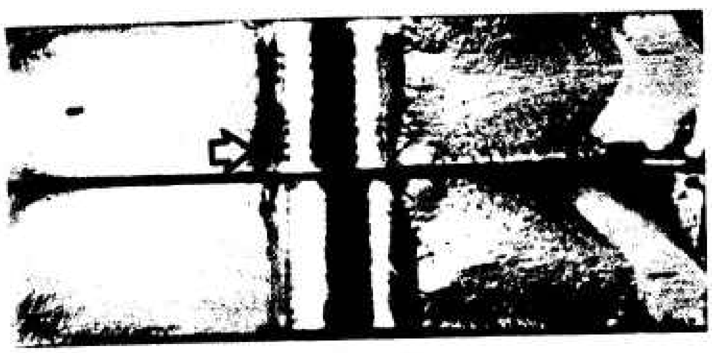
Specimen 21



Specimen 24



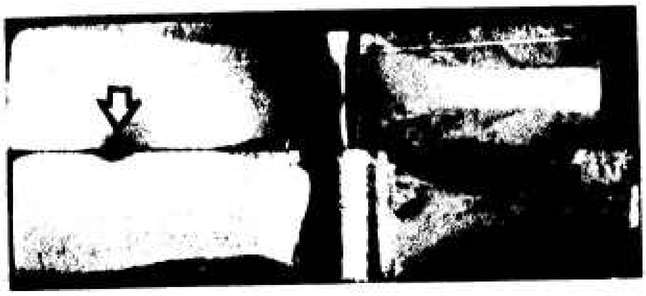
Specimen 4



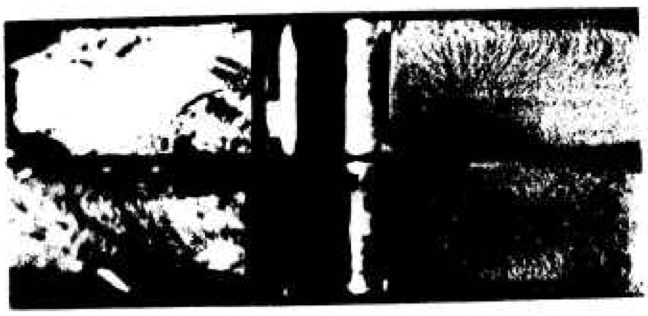
Specimen 4-2

GP71-0879-9

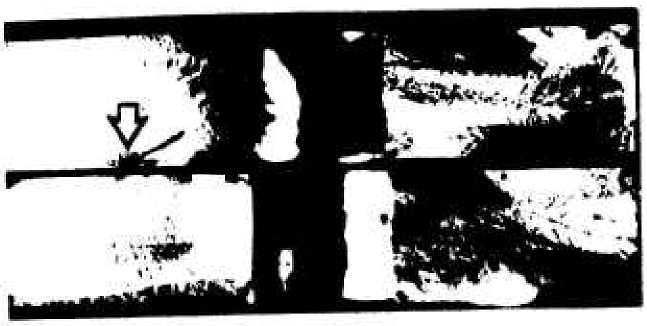
Specimen 6



Specimen 25



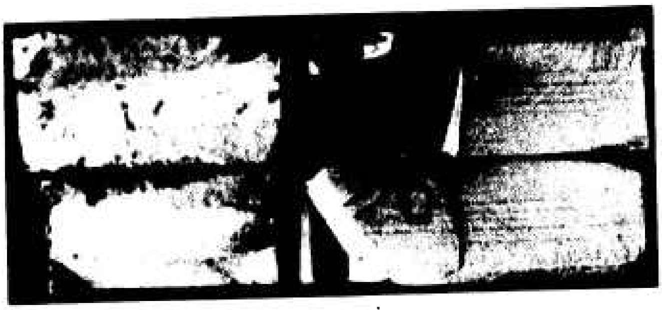
Specimen 26



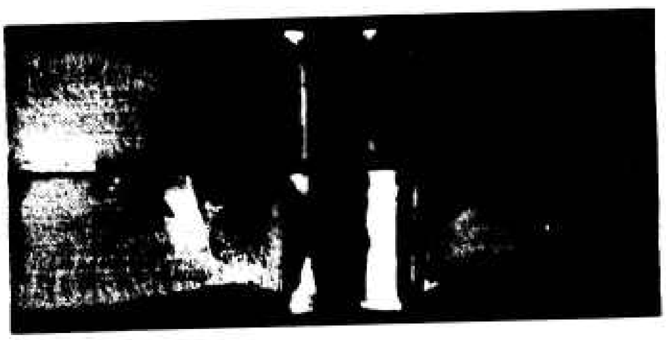
Specimen 27

GP71-0879-10

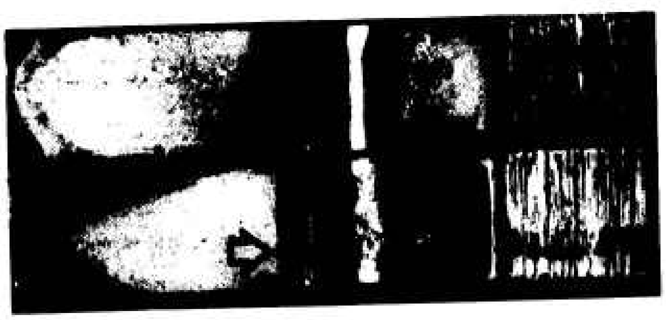
Specimen 28



Specimen 29

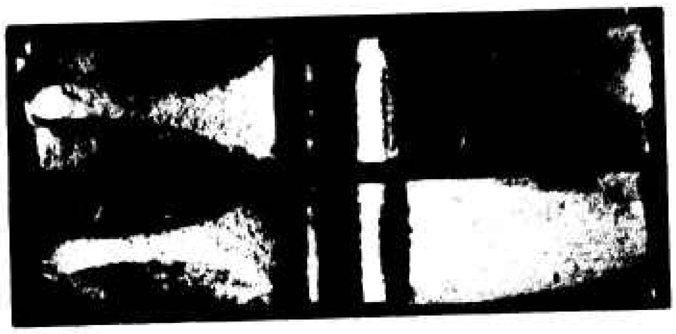


Specimen 30-2

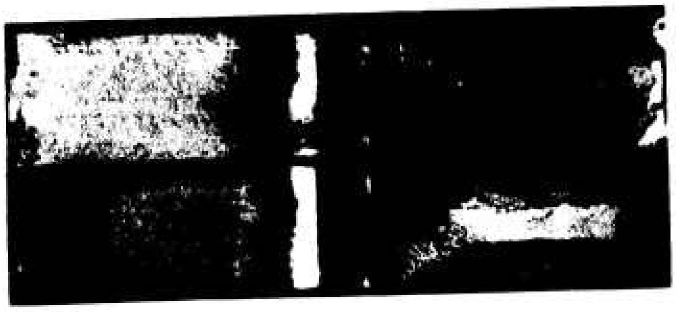


Specimen 31

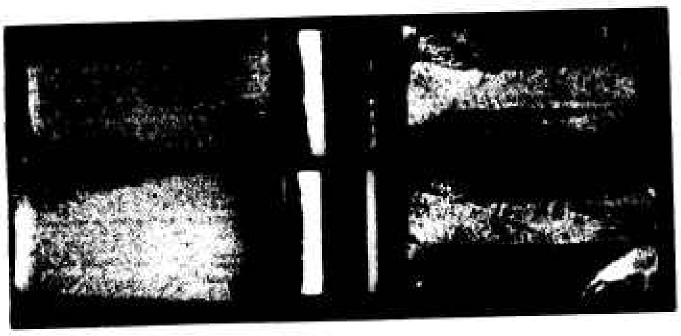
GP71-0879-11



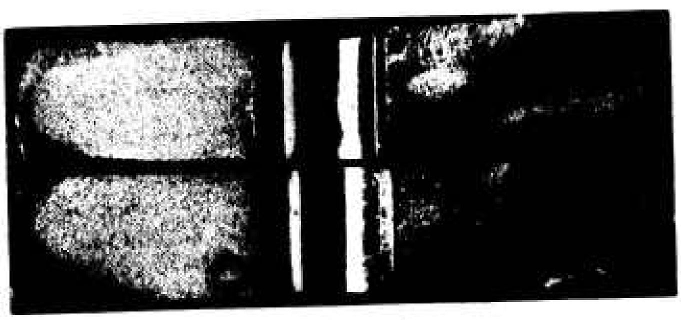
Specimen 32



Specimen 33



Specimen 34

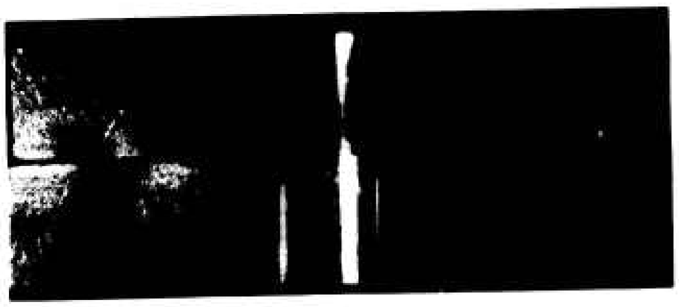


Specimen 35

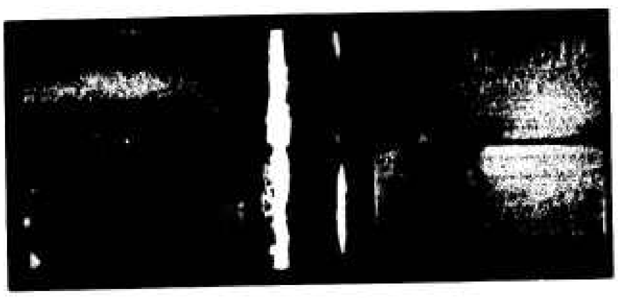
GP71-0879-12

Specimen 36

Specimen 37

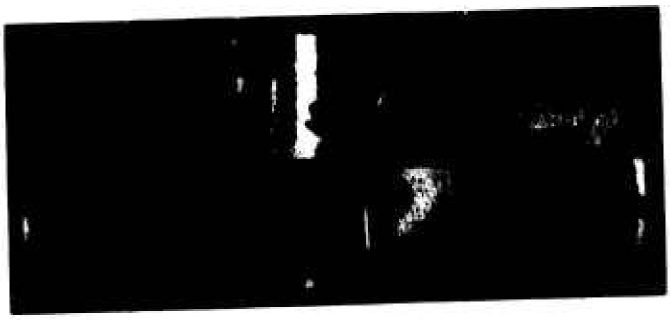


Specimen 39

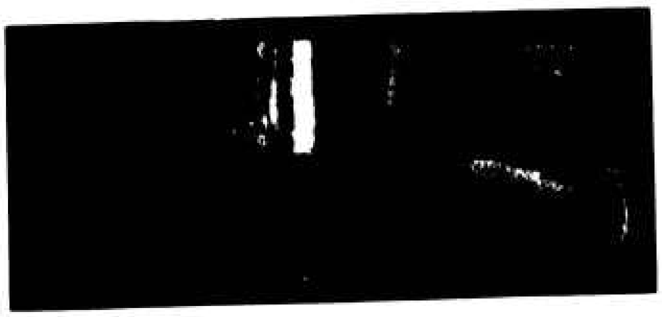


Specimen 40

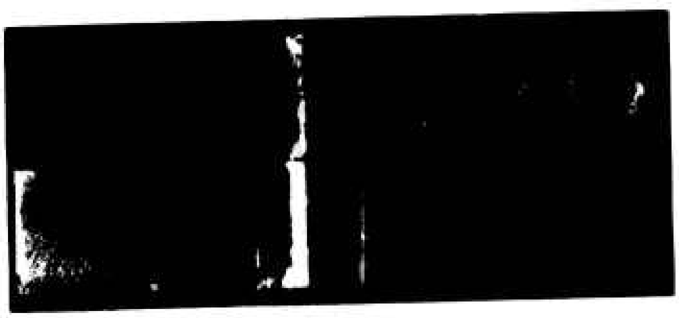
GP71-0879-13



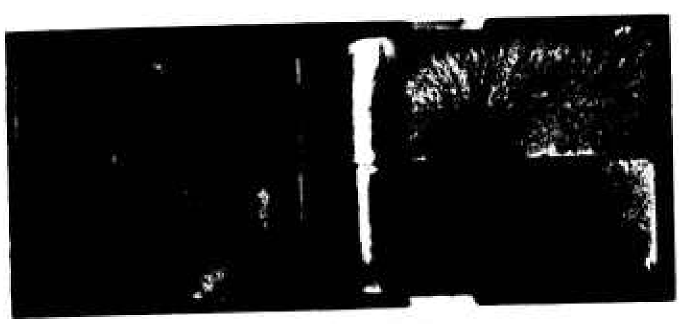
Specimen 38



Specimen 41

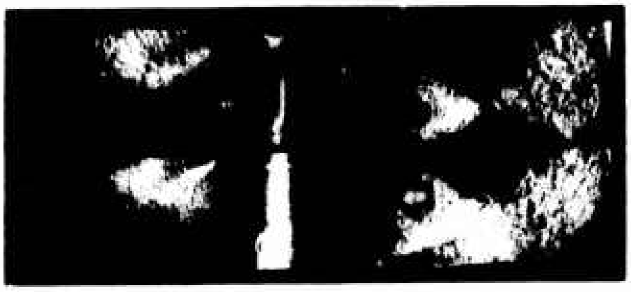


Specimen 43

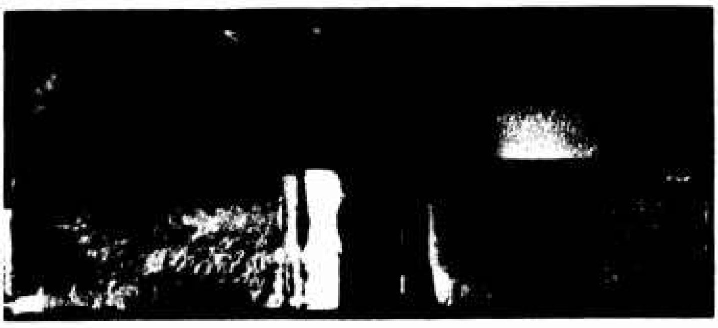


Specimen 44

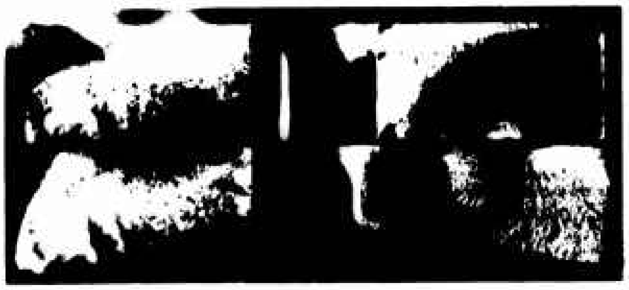
GP71-0879-14



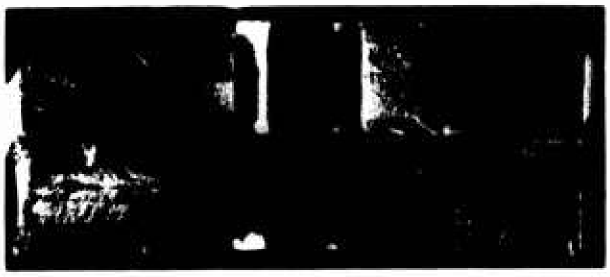
Specimen 46



Specimen 47



Specimen 48



Specimen 43A

GP71-0879-15

APPENDIX D - COATING DATA

COATING DATA SHEET

COATING: Watervliet Anodize

TYPE: Anodic

DESCRIPTION: Anodized in alkaline electrolyte containing titanium dioxide.

MAX. PROCESS TEMP. (^{o}F): 70

THICKNESS: .0002 inch

HARDNESS: Unknown

ADHESION: Good

SOURCE: Watervliet Arsenal

STATUS: Production

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: This patented process was the forerunner of several other commercial processes and has been tested by many laboratories.

REFERENCES: Pochily, Theodore M., "Process for Anodizing Titanium," Tech. Report WVT-6605, Benet Laboratories, Watervliet Arsenal, Watervliet, N. Y., April 1966.

COATING DATA SHEET

COATING: Tiodize

TYPE: Anodic coating

DESCRIPTION: Anodized in a proprietary alkaline solution

MAX. PROCESS TEMP. (°F): 200 (estimated)

THICKNESS: .0002 inch

HARDNESS: Unknown

ADHESION: Good

SOURCE: Tiodize Co., Inc.

STATUS: Production

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Thicker deposits can be obtained but the top layer is a loose film with no useful properties, is normally removed ultrasonically.

REFERENCES: Tiodize Co., Inc., de Laat, Frans G. A., and Adams, T., "Inhibiting the Wear and Galling Characteristics of Titanium" March 1968, Western Metal and Tool Conference, ASM.

COATING DATA SHEET

COATING: MCAIR Anodize

TYPE: Anodic coat

DESCRIPTION: Anodized in a proprietary acid electrolyte

MAX. PROCESS TEMP. (°F): 110

THICKNESS: .0002 inch

HARDNESS: Unknown

ADHESION: Good

SOURCE: MCAIR

STATUS: Laboratory

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Decreases tension-tension fatigue properties.

COMMENTS: This process has shown excellent results as a bond coat for solid film lubricant.

REFERENCES: "Protection of Titanium at Elevated Temperatures," MCAIR Engineering Study Authorization, E6620-337, November 1967; MCAIR Process Bulletin 3-224, "Anodizing of Titanium Alloys."

COATING DATA SHEET

COATING: "Ti-Cote"

TYPE: Anodic coat

DESCRIPTION: Anodized in a proprietary alkaline electrolyte

MAX. PROCESS TEMP. (^{o}F): 200 (estimated)

THICKNESS: .0001 inch, max.

HARDNESS: Unknown

ADHESION: Good

SOURCE: Electrofilm, Inc.

STATUS: Production

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Claimed to be no drop in fatigue properties in rotating beam fatigue tests.

COMMENTS: This coating has been used on the bore of a hydraulic actuator in the F-111. It is claimed to avoid the loose surface deposit sometimes found on other anodic films.

REFERENCES: Electrofilm, Inc.

COATING DATA SHEET

COATING: Oxide

TYPE: Chemical conversion

DESCRIPTION: Produced from molten bath of lithium carbonate. Coating has been identified as $TiO_{1.9}$.

MAX. PROCESS TEMP. (°F): 1475 - 3 hr.

THICKNESS: Thin

HARDNESS: 700-950 VHN (5 kg.)

ADHESION: Good in 105° bend

SOURCE: TMCA

STATUS: Pilot

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Passed sliding wear tests at 25 KSI loads but failed early in test runs at higher loads. High process temperature is a serious drawback.

REFERENCES: MCAIR "Titanium Processing Technology," Report H425, 1 Sept. 1969

COATING DATA SHEET

COATING: Borate-fluoride

TYPE: Chemical conversion

DESCRIPTION: Produced in an aqueous solution containing $Na_2B_4O_7 \cdot 10H_2O$, 18 $KF \cdot 2H_2O$, and HF

MAX. PROCESS TEMP. (°F): 185

THICKNESS: Thin

HARDNESS: Unknown

ADHESION: Good

SOURCE: TMCA, et. al.

STATUS: Production

COST: Low

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Used for lubrication of titanium wire in drawing. Probable use is as bond coat for solid lubricant.

REFERENCES: Kostman, Stanley J., "The Wear and Lubrication of Titanium" Project BM-06-1, First Summary Report; Conference Report, Stanley J. Kostman, et. al., at McDonnell, 21 Oct. 1966; ASM Metals Handbook, 8th Edition, Vol. 2, American Society for Metals, Metals Park, Ohio (1964).

COATING DATA SHEET

COATING: Phosphate-fluoride

TYPE: Chemical conversion

DESCRIPTION: Produced in bath composed of Tribasic Sodium Phosphate, Potassium Fluoride, and Hydrofluoric Acid

MAX. PROCESS TEMP. (^{o}F): 195

THICKNESS: Thin

HARDNESS: Unknown

ADHESION: Good

SOURCE: General Dynamics, et. al.

STATUS: Production

COST: Relatively low

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Prone to formation of loose crystalline deposit. This type of coating recommended for bond coat for solid lubricants.

REFERENCES: Kostman, Stanley J., "The Wear and Lubrication of Titanium" Project BM-06-1, First Summary Report; Conference Report, Stanley J. Kostman, et. al., at McDonnell, 21 Oct. 1966; General Dynamics FW Report FPS-0116A, "Application of Conversion Coating on Titanium Alloys," 19 Sept. 1969.

COATING DATA SHEET

COATING: Oxides

TYPE: Molten Salt Bath

DESCRIPTION: Produced from molten borax baths

MAX. PROCESS TEMP. (^{o}F): 1400 and higher

THICKNESS: Thin

HARDNESS: 1300-1500 VHN

ADHESION: Unknown

SOURCE: Armour Research Foundation

STATUS: Laboratory

COST: Expected to be high

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: The process has been under experimentation in Britain, Japan, and Russia, as well as the U. S.

REFERENCES: "Surface Treatment of Titanium" Summary of Round Table Meeting, Watertown Arsenal - Report No. AD628-992, Defense Documentation Center, 20 May 1952.

COATING DATA SHEET

COATING: Molykote 106

TYPE: Solid Film Lubricant - MoS_2

DESCRIPTION: MoS_2 in an epoxy resin will withstand 500°F

MAX. PROCESS TEMP. (°F): 350

THICKNESS: .0002-.0005 inch

HARDNESS: --

ADHESION: Excellent

SOURCE: Dow Corning Corporation

STATUS: Production

COST: Same as on other production parts

EFFECT ON PROPERTIES OF BASIS METAL: Expected to have no effect.

COMMENTS: This material has best adhesion and wear life of all dry film lubes tested at MCAIR. With proper surface pretreatment, it is excellent wear coating on titanium. Coefficient of friction less than .1.

REFERENCES: Tucker, M. et. al., "Dry Film Lubricant Evaluation," MCAIR T.R. 513-340, July 1962 and Pfeffer, R., "Development of Epoxy Resin Based Solid Film Lubricant," MCAIR T.R. 513-587, December 1966.

COATING DATA SHEET

COATING: Wright-Patterson Developed Lubricant, AFSL-41

TYPE: Solid Film Lubricant

DESCRIPTION: Air dry silicone resin with MoS_2 and Sb_2O_3 pigment.

MAX. PROCESS TEMP. (°F): Air dry

THICKNESS: .0002-.0005 inch

HARDNESS: --

ADHESION: Good

SOURCE: Not available yet - all material has been made in laboratory at WPAFB

STATUS: Laboratory

COST: Not established

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Metal surface must be grit blasted for adhesion. The wear life tests performed at WPAFB show much better wear life at 700°F than commercially available dry film lube. The wear life at room temperature and at 500°F is same as commercial lubricants. The fluid resistance of this material is questionable.

REFERENCES: Communication with R. McConnell (MANL), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, June 1970.

COATING DATA SHEET

COATING: Electrofilm 2306

TYPE: Solid Film Lubricant - Graphite

DESCRIPTION: Graphite and MoS_2 in sodium silicate binder

MAX. PROCESS TEMP. (°F): 400

THICKNESS: .0002-.0005 inch

HARDNESS: --

ADHESION: Good

SOURCE: Electrofilm, Inc.

STATUS: Production

COST: Slightly more than organic solid film lubricants

EFFECT ON PROPERTIES OF BASIS METAL: Expected to have no effect.

COMMENTS: Used on spacecraft because of performance in a vacuum. Can accelerate corrosion on some surfaces. Higher coefficient of friction than organic solid film lubes.

REFERENCES: Bradly, T. P., "Evaluation of Dry Film Lubricants," MCAIR T.R. 052-044.02, July 1963 and Pfeffer, R., "Development of Epoxy Resin Based Solid Film Lubricant," MCAIR T.R. 513-587, December 1966.

COATING DATA SHEET

COATING: Teflon-S 954-100 Series

TYPE: Solid Film Lubricant - TFE

DESCRIPTION: Fluorocarbon resin and modifiers

MAX. PROCESS TEMP. (°F): 450

THICKNESS: .0015-.0030 inch

HARDNESS: Very soft

ADHESION: Good

SOURCE: DuPont

STATUS: Not used in production at MCAIR - but widely used in commercial market

COST: More expensive than organic solid film lubricants

EFFECT ON PROPERTIES OF BASIS METAL: Expected to have no effect.

COMMENTS: Very good lubricant at low loads. Coefficient of friction less than .1. Maximum temperature use is 350°F. Material will cold flow under high static loads.

REFERENCES: E. I. duPont Company

COATING DATA SHEET

COATING: Nickel

TYPE: Electroplate

DESCRIPTION: Electrolytically deposited on basis metal prepared by proprietary process

MAX. PROCESS TEMP. (°F): 1000

THICKNESS: .0005 inch and thicker

HARDNESS: Low (hard chrome overplate will raise hardness to 800 VHN)

ADHESION: Good

SOURCE: MCAIR

STATUS: Laboratory

COST: Comparable to commercial nickel plating steel parts

EFFECT ON PROPERTIES OF BASIS METAL: Decreases fatigue endurance limit

COMMENTS: Can be used as base coat for hard chromium. Many platers have investigated plating on titanium and have met the universal problem of poor adherence. This process is the only one to our knowledge capable of such bond.

REFERENCES: Keeser, H. M., "Nickel Plating on Titanium," T.R. 513-853, 19 August 1969.

COATING DATA SHEET

COATING: Nickel

TYPE: Electroless

DESCRIPTION: Nickel phosphorus coating deposited from aqueous solution with hypophosphite as reducing agent.

MAX. PROCESS TEMP. (°F): 600 (post-plate bake)

THICKNESS: .0002-.001 inch

HARDNESS: 900 VHN

ADHESION: Good

SOURCE: General American Research Div.

STATUS: Laboratory

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Electroless deposits have the capability of producing uniform thickness over irregular shapes. Bend tests have shown good bond.

REFERENCES: Telecon Report, D. J. Padberg-K. Parker (General American Transportation Corporation), 8 April 1970; Beck, W. and Danovich, J. F., "Wear Studies of Titanium Coated with Electroless Nickel," Naval Air Dev. Center, Johnsville, Pa., Report No. NADC-MA-6914, Oct. 1969; Cowan, Del Grasso, Mattavi, McGivern, "Development of Intermetallic Coated Titanium Gears," SAMPE Symposium, Los Angeles, Calif., May 1969.

COATING DATA SHEET

COATING: Zinc

TYPE: Electroplated and electroless plated

DESCRIPTION: Deposited from aqueous solution

MAX. PROCESS TEMP. (°F): Unknown

THICKNESS: .0001-.002 inch

HARDNESS: Low

ADHESION: Fair in thin deposits

SOURCE: TMCA

STATUS: Laboratory

COST: Unknown

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Used in thin deposit for bond coat under other metals. Thick (.002) deposit used in wear tests.

REFERENCES: Kostman, Stanley J., "The Wear and Lubrication of Titanium," Project BM-06-1, First Summary Report, Titanium Metals Corp. of America, 30 Sept. 1966.

COATING DATA SHEET

COATING: Chromium, "TIBON" process

TYPE: Electroplated

DESCRIPTION: Electroplate on titanium by proprietary process

MAX. PROCESS TEMP. (°F): Unknown

THICKNESS: .0005 inch and up

HARDNESS: 900 VHN and higher

ADHESION: Good

SOURCE: Superior Plating Company

STATUS: Laboratory

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Decreased fatigue life in tests at MCAIR. Rotating beam tests are reported to show no decrease in fatigue resistance.

COMMENTS: This is the only chromium-on-titanium process that was able to pass the bend-to-break bond test. The process is proprietary but is thought to include a diffusion heat treatment. Tests on Ti-6Al-4V yielded serious reduction in fatigue life.

REFERENCES: Hatfield, D. C., "Effect of Various Coatings on Fatigue Properties of Titanium," Tech. Memo No. 256.1021, Sept. 1970.

COATING DATA SHEET

COATING: Chromium (et. al.)

TYPE: Sputtering

DESCRIPTION: Ion bombardment of material to be deposited. The metal to be deposited is the cathode.

MAX. PROCESS TEMP. (°F): Less than 250

THICKNESS: Angstrom units (10^{-8} cm)

HARDNESS: Depends on material

ADHESION: Fair to good

SOURCE: Weston Instruments, Inc.

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Very slow process, impractical for structures.

REFERENCES: Matley, T. and Luedman, R. T., "Vacuum Sputtering Process for Chromium Plating Titanium Alloys," Report No. SX-12074, Weston Instruments, Inc., Newark, N.J., Sept. 1967; Hassion, "Sputtering Intermediates on Titanium to Improve Adhesion of Electrodeposited Chromium," Springfield Armory, Report AD642-780, April 1966.

COATING DATA SHEET

COATING: Aluminum

TYPE: Physical vapor deposition

DESCRIPTION: Plating metal is vaporized, in a vacuum, and condensed on the workpiece. No high-voltage system is used.

MAX. PROCESS TEMP. (°F): 300

THICKNESS: .0003 inch and up

HARDNESS: R_c 68 (hard coated)

ADHESION: Fair

SOURCE: MCAIR, et. al.

STATUS: Production

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: No effect.

COMMENTS: Aluminum can be hard anodized.

REFERENCES: Steube, K. E., "Hard Anodize of Aluminum Coated Titanium for Wear Applications," MCAIR Report 513-909, 28 July 1970.

COATING DATA SHEET

COATING: Chromium, Molybdenum

TYPE: Chemical Vapor Deposition

DESCRIPTION: Dissociation of metal bearing vapor which yields a solid deposit and gaseous by-products.

MAX. PROCESS TEMP. (°F): 1475 or higher

THICKNESS: .0003 inch and up

HARDNESS: 500 VHN and higher

ADHESION: Good

SOURCE: General Technologies Corp., et. al.

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Temperature required for deposition depends on the decomposition temperature of the chromium or molybdenum compound used.

REFERENCES: Keeser, H. M., "Chemical Vapor Deposition on Titanium and Steel," MCAIR Report T.R. 604-130.22, 13 June 1966.

COATING DATA SHEET

COATING: Aluminum

TYPE: IVD

DESCRIPTION: Deposition of ionized atoms accelerated toward the substrate by an applied dc potential. The substrate is the cathode of a high voltage system.

MAX. PROCESS TEMP. (°F): 300

THICKNESS: .0003 inch and greater

HARDNESS: R_c 68 (hard coated)

ADHESION: Good

SOURCE: MCAIR

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Aluminum can be hard anodized

REFERENCES: Klein, A. A., "Deposition and Evaluation of Functional IVD Coatings," MCAIR Report G-299, 30 Oct. 1968 and Steube, K. E., "Hard Anodize of Aluminum Coated Titanium for Wear Applications," MCAIR Report 513-909, 28 July 1970.

COATING DATA SHEET

COATING: "TIDURAN"

TYPE: Diffusion

DESCRIPTION: Diffusion of carbon and nitrogen into surface from molten salt

MAX. PROCESS TEMP. (°F): 1400

THICKNESS: .0001-.0004 inch

HARDNESS: 300-500 KHN (200 gm)

ADHESION: Good

SOURCE: Kolene Corp.

STATUS: Production

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Coating has 2 layers, the top one is loosely adherent and should be removed before use. High temperature, low hardness, thin coat make it a poor candidate for fretting applications in aircraft.

REFERENCES: Hatfield, D. C., "Effect of Various Coatings on Fatigue Properties of Titanium," Tech. Memo No. 256.1021, Sept. 1970; Gregory, C., "Fretting Tests for Comparison of Various Coatings on Titanium," MCAIR Report T.R. 513-924, 29 June 1970.

COATING DATA SHEET

COATING: Boronizing

TYPE: Diffusion

DESCRIPTION: High temperature diffusion of boron from surrounding medium into titanium surface. Various investigators have used borax or solid boron as the pack material.

MAX. PROCESS TEMP. (°F): 1830-2100

THICKNESS: .0001-.0005 inch

HARDNESS: 1000-1150 VHN

ADHESION: Fair

SOURCE:

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: This process has been studied by Russian investigators as well as various U.S.

REFERENCES: Weltzin, R. D., "Surface Treatment of Ti-6Al-4V for Impact-Fatigue and Wear Resistance," Proceedings of ASTM Symposium, Los Angeles, Calif., 18 April 1967, ASTM Special Technical Publication No. 432; "Surface Impregnation of Steel with Boron from the Gas Phase," April 1959, Metallovednie i Term. Ohrabotka Mettalow; "Chromizing and Boronizing of Steel with Induction Heating," April 1956, Metallovednie i Term. Ohrabotka Mettalov.

COATING DATA SHEET

COATING: Carburizing

TYPE: High temperature diffusion

DESCRIPTION: Carbon diffused into surface. Pack method and carbon bearing gases can be used.

MAX. PROCESS TEMP. (°F): 1800

THICKNESS: .0002-.0008 inch

HARDNESS: Unknown

ADHESION: Poor

SOURCE:

STATUS:

COST:

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Old tests show the case produced was brittle and thin, not usable.

REFERENCES: Mallett, Manley W., "Surface Treatments for Titanium Alloys," NASA Technical Memorandum NASA TMX-53429, Oct. 1965 and Wood, R. A., "Surface Treatment of Titanium," DMIC Technical Note, 15 March 1965.

COATING DATA SHEET

COATING: Cyanide

TYPE: High temperature diffusion

DESCRIPTION: Nitrogen and carbon diffused into surface in a molten cyanide salt bath

MAX. PROCESS TEMP. (°F): 1470

THICKNESS: Unknown

HARDNESS: 400-600 VHN

ADHESION: Good

SOURCE: Lucas Research Centre, England

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Reduces fatigue properties

COMMENTS: Cyanide salts dissolve titanium. As a result, this process is not recommended.

REFERENCES: Mitchell, E., and Brotherton, P. J., "Surface Treatments for Improving the Wear-Resistance and Friction Properties of Titanium and its Alloys," Journal of the Institute of Metals, Vol. 93, July 1965.

COATING DATA SHEET

COATING: Nitride

TYPE: Diffusion

DESCRIPTION: High temperature diffusion of nitrogen into the titanium surface. Ammonia or nitrogen used as atmosphere.

MAX. PROCESS TEMP. (°F): 1560-1830

THICKNESS: .0005-.002 inch

HARDNESS: 700-1500 VHN

ADHESION: Good

SOURCE: Armour Research Foundation, et. al.

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: For practical purposes, nitriding requires temperatures over 1400 F for about 16 hours. This could seriously affect mechanical properties, shape, etc. Some reports claim a decrease in fatigue properties.

REFERENCES: "Surface Treatment of Titanium", Summary of Round Table Meeting, Watertown Arsenal - Report No. AD628-992, Defense Documentation Center, 20 May 1952; Weltzin, R. D., "Surface Treatment of Ti-6Al-4V for Impact-Fatigue and Wear Resistance," Proceedings of ASTM Symp., Los Angeles, Calif., 18 April 1967, ASTM Special Technical Publication No. 432; and Mitchell, E., and Brotherton, P. J., "Surface Treatments for Improving the Wear-Resistance and Friction Properties of Titanium and its Alloys," Journal of the Institute of Metals, Vol. 93, July 1965.

COATING DATA SHEET

COATING: Aluminum

TYPE: Diffusion-Metalliding

DESCRIPTION: Electrolytic deposition in a molten salt bath

MAX. PROCESS TEMP. (°F): 1325 and above

THICKNESS: .001-.020 inch

HARDNESS: Unknown

ADHESION: Good

SOURCE: General Motors Corp.

STATUS: Laboratory

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: .0005-.0010 diffusion layer is expected to affect fatigue properties.

REFERENCES: General Motors Corp., Allison Div.; "The Characteristics and Uses of Aluminum Coatings on Titanium and Titanium Alloys," Battelle Memorial Institute, 12 Oct. 1956.

COATING DATA SHEET

COATING: Chromium, Aluminum

TYPE: Diffusion-Metalliding

DESCRIPTION: High temperature electrolytic diffusion in a molten salt bath. The diffusing metal serves as the anode.

MAX. PROCESS TEMP. (°F): 1400-2000

THICKNESS: .0005-.002 inch

HARDNESS: Depends on amount of diffusion and material deposited.

ADHESION: Good

SOURCE: General Technologies Corp.

STATUS: Production

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Unknown

COMMENTS: Because of the diffused zone, this process is expected to decrease fatigue limit. High temperature makes it less attractive.

REFERENCES: General Technologies Corp., 1821 Michael Faraday Dr., Reston, Va.

COATING DATA SHEET

COATING: Tungsten Carbide (commonly mixed with cobalt)

TYPE: Metallized

DESCRIPTION: Detonation gun sprayed - molten particles travel at 2500 fps due to a combustion reaction. Gun temperature approaches 6000°F.

MAX. PROCESS TEMP. (°F): 300 (part being coated)

THICKNESS: .003 inch and up

HARDNESS: 1150 VHN

ADHESION: Fair

SOURCE: Union Carbide Corporation

STATUS: Production

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Decreased fatigue life.

COMMENTS: Most dense of all metallizing processes; best bond strength, although still will not pass severe bend tests because of brittle nature of deposits and lack of metallurgical bond.

REFERENCES: Union Carbide; Miller, R. B., "Wear Resistant Coatings for Titanium," MCAIR Material & Process Dev. R&D Rpt. No. 90, 30 Dec. 1966; Gruer, V. J., "Improved Wear Resistance Methods for Titanium," MCAIR Rpt. No. G281, 15 May 1968.

COATING DATA SHEET

COATING: Tungsten Carbide; Molybdenum; Copper-Nickel-Indium

TYPE: Metallized

DESCRIPTION: Plasma flame sprayed - powder is fed into a high velocity inert gas stream (produced from a non-transferred electric arc) of 30,000°F.

MAX. PROCESS TEMP. (°F): 300 (part being coated)

THICKNESS: .003 inch and up

HARDNESS: 500 VHN and higher, depending on coating

ADHESION: Fair

SOURCE: METCO, Inc., Union Carbide, St. Louis Metallizing, et. al.

STATUS: Production

COST: High

EFFECT ON PROPERTIES OF BASIS METAL: Decreased fatigue life

COMMENTS: Less porous than oxy-acetylene deposits. Bond is not metallurgical. Excellent wear properties. Cu-Ni-In is used extensively on engine parts subject to fretting.

REFERENCES: Metco, Inc.; Gruer, V. J., "Improved Wear Resistance Methods for Titanium," MCAIR Report No. G281, 15 May 1968.

COATING DATA SHEET

COATING: Molybdenum, Bronze

TYPE: Metallized

DESCRIPTION: Oxy-acetylene flame sprayed - wire or powder fed into flame which produces molten particles and propels these particles to the substrate. Typical particle velocity is 300/550 fps.

MAX. PROCESS TEMP. (°F): 300 (part being coated)

THICKNESS: .003 inch and up

HARDNESS: Molybdenum - 800 VHN; Bronze-R_B 80

ADHESION: Fair

SOURCE: METCO, Inc.; St. Louis Metallizing, et. al.

STATUS: Production

COST: Moderate

EFFECT ON PROPERTIES OF BASIS METAL: Decreased fatigue life

COMMENTS: Metallized coatings do not have a metallurgical bond, are brittle and will not withstand a severe bend test. Excellent wear properties depending on material deposited.

REFERENCES: Hatfield, D. C., "Effect of Various Coatings on Fatigue Properties of Titanium," Tech. Memo No. 256.1021, Sept. 1970 and Lum, D. W., "Titanium Processing Technology-Wear Coating," Report H425, 1 Sept. 1969.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) McDonnell Aircraft Company P.O. Box 516 St. Louis, Missouri 63166	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

FRETTING RESISTANT COATINGS FOR TITANIUM ALLOYS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Technical Report, 18 May 1970 to 18 June 1971

5. AUTHOR(S) (First name, middle initial, last name)

Donulus J. Padberg

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1971	105	3

8a. CONTRACT OR GRANT NO. F33615-70-C-1538 b. PROJECT NO. 7312 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) N/A 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFML-TR-71-184

10. DISTRIBUTION STATEMENT

Distribution limited to U.S. Government agencies only; Test and Evaluation; 13 September 1971. Other requests for this document must be referred to the Metals and Ceramics Div., AF Materials Laboratory, Wright-Patterson AFB, Ohio.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
N/A	Metals and Ceramics Division Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

This report describes a program undertaken to establish the effect of airframe design parameters upon the severity of fretting in titanium structures and to determine the ability of selected coatings to prevent fretting induced fatigue failures. The program was performed in three tasks.

Task I began with a survey of aircraft structures establishing the design limits of those parameters which can influence fretting. A test specimen was designed to simulate a structural joint and a series of fatigue tests was performed to determine the conditions most conducive to fretting initiated failure. It was found that at low stress levels and using tapered interference fit fasteners, the number of fatigue cycles accumulated to the point that fractures originated from fretting damage. These latter parameters were chosen for test of coated specimens in Task III.

Task II consisted of a survey of titanium coatings technology and testing and selection of three coatings for use in Task III. On the basis of their properties and minimal degradation of Ti-6Al-6V-2Sn fatigue resistance, a chemical conversion coating and a commercial anodize coating were chosen along with a dry film lubricant.

Task III consisted of fatigue tests of Ti-6Al-6V-2Sn specimens protected by the coatings from Task II. The coatings essentially eliminated the fretting induced fatigue failures of Task I. Final coating performance verification tests on Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo specimens demonstrated the same improvement using dry film lubricant applied to a shot peened surface.

DD FORM 1 NOV 65 1473

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fretting Resistant Coatings						
Fretting-Fatigue						
Titanium Coatings						
Fatigue Life Impairment						
Titanium Surface Treatments						

Unclassified

Security Classification